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TURBIDITY CRITERIA DOCUMENT

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The Office of Drinking Water (ODW), U.S. Environmental Protection Agency has prepared a criteria document on turbidity. This document discusses the turbidity occurrence and characteristics, direct health effects, indirect health effects, turbidity effects on disinfection demand, turbidity interference with coliform detection, turbidity measurement and examination of turbidity as a potential regulation.

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TURBIDITY CRITERIA DOCUMENT SUMMARY

Turbidity has been used as an indicator of drinking water quality and filtration efficiency for many decades. It is an optical measurement of suspended particles such as clay, silt, finely divided organic and inorganic matter, and microorganisms. Turbidity is an imprecise measure, comprised of a wide variety of particles from a wide variety of sources, and it provides no information about the weight, volume, or composition of the particles present. For example, 50 mg kaolinite/liter produces a turbidity of about 80 NTU, while 50 mg humic acid/liter produces a turbidity of only slightly more than 3 NTU.

There are several reasons for measuring turbidity. Some particles may have a direct health effect. Foremost among these are pathogenic organisms and possibly asbestos fibers. Nevertheless, relatively few particles are known to have a direct health effect. Particles may also have an indirect health effect through their ability to adsorb toxic material from water. Both inorganic and organic particles may serve as adsorption sites for these materials. Few data on the extent and potential human health significance of this process as it relates to drinking water are available.

Turbidity can interfere with total coliform analysis by the membrane filter technique. Particles may clog membrane pores; entrap coliforms, preventing colony formation; and support high densities of heterotrophic bacteria which may interfere with coliform growth. Several studies have shown significantly lower coliform levels by the membrane filter technique compared to the multiple tube fermentation technique, where turbidity was implicated as the major factor in the difference. Interference has been demonstrated at turbidity levels above 2 NTU. Data are not available to assess whether levels below 1 NTU can also interfere.

Particles also can protect pathogenic microorganisms from disinfection. They may exert a substantial disinfectant demand in some circumstances, but generally it is estimated that particulate matter in raw water causes less than 10% of the disinfectant demand. About 90% is associated with the dissolved fraction. Nevertheless, there is apparently a correlation between turbidity levels and dissolved substance levels, and as raw water turbidity increases, chlorine demand also increases. High chlorine demand water interferes with disinfection and prevents maintenance of an effective disinfectant agent throughout the distribution system.

A more important way particles can protect microorganisms from disinfection is by particle-microorganism complexes. For disinfection to be effective, there must be contact between the disinfectant and the organisms. Particles may adsorb or encase microorganisms in water, thereby reducing or preventing disinfectant contact. This effect is most significant for viruses, which are smaller than bacteria and protozoa and more subject to particulate surface charges. Particles of concern in this context are greater than 0.03 um. Disinfection efficiency depends to a large extent on the nature of the particles. Several disinfection studies with viruses have demonstrated that, in general, inorganic particles such as alum floc, calcium carbonate, aluminum phosphate, kaolin, and bentonite clay fail to confer significant protection at levels of approximately 1-10 NTU. This inability of inorganic particles to protect viruses was observed for chlorine, chlorine dioxide, and ozone. A few exceptions have been reported, but in all cases disinfection kinetics were essentially first order.

In contrast, organic particles can confer protection. In disinfection studies using viruses associated with cell debris or feces, and coliforms associated with primary wastewater effluent solids, inactivation rates depart substantially from first order kinetics. There is an initial rapid die-off which gradually decreases, eventually showing little or no further decline. Inactivation times may be increased by an order of magnitude or greater. In several studies, this effect was observed for turbidity levels in the range of 1 to 5 NTU. It is significant that those particles that appear to offer the most protection (solids in wastewater effluents) are also those most likely to be associated with fecal pathogens. Organic matter reduced inactivation rates for chlorine and ozone. In a study where chlorine dioxide was used, inactivation rates were not affected; the significance of this has not been investigated. In general, data indicate that in wastewater the proportion of viruses and coliforms associated with solids is probably low. This may also be true of drinking water, although solid-associated viruses from wastewater may survive much longer in ambient water than unassociated viruses, thereby increasing their relative proportion considerably.

The problems associated with high turbidity levels can be minimized by the use of filtration. About the turn of this century, it was found that the incidence of cholera and typhoid fever could be reduced by filtering water, even in the absence of disinfection. Although no turbidity standards were in effect at that time, the data showed conclusively that reduction of the amount of particulate matter in water reduced the incidence of waterborne disease. Turbidity removal also enhances the effectiveness of disinfection and removes toxic substance-bearing particles. This suggested that turbidity could be used to evaluate drinking water quality. The first turbidity standards in the United States were promulgated in 1914 by the U.S. Public Health Service.

That removal of particles could control waterborne disease outbreaks was supported by a review of national outbreak data between 1946 and 1980. In this examination, outbreaks were geographically distributed by State and rate-based according to the number of water systems in each State. A comparison was then made between the States with a low outbreak rate and those with a high rate by computing ratios of water systems using treatment (filtration plus disinfection) of surface water as opposed to those using untreated (includes disinfection only) surface water. Comparison of the ratios indicated that States exhibiting a low outbreak rate had a much higher ratio (four to one) of systems providing treatment. These observations provide indirect evidence that inclusion of particle removal processes in drinking water treatment reduces the possibility of a waterborne disease outbreak.

The relationship between turbidity removal and pathogen removal depends upon the type of filtration used. For rapid granular media filtration, greater particulate removal is associated with greater removal of microorganisms, including Giardia cysts. Research with a variety of waters generally having raw water turbidities less than 10 NTU has shown that when rapid granular media-filtered water was 0.10 NTU or lower, greater than 99% removal of cysts was achieved. A 1 NTU level was not sufficient for good cyst removal.

For diatomaceous earth filtration, the main mechanism for particle removal is straining. Most turbidity-causing particles tend to be smaller than Giardia cysts, and research has shown repeatedly that cyst removals of greater than 99.9% can be achieved even though turbidity removal is variable. The extent of turbidity removal, however, is usually lower and corresponds more closely with that of bacteria and viruses.

Slow sand filters remove microbial contamination primarily by biological means rather than by physico-chemical mechanisms. This type of removal is often less effective in removing turbidity-causing particles. Thus removal of pathogens may not correspond to turbidity removal, reducing the value of turbidity as an indicator of water quality when slow sand filters are used.

Analytical techniques for measuring turbidity are available. The nephelometric method is normally used for potable water, and this procedure is described in Standard Methods for the Examination of Water and Wastewater. Particles can also be characterized as to size and number by particle counters and particle size analyzers.

The data indicate that turbidity monitoring for potable water is worthwhile, and that a health goal of 0.1 NTU is justified. This is primarily based upon the premise that lower turbidity levels represent less health risk. Several studies have demonstrated efficient removals of Giardia cysts at 0.1 NTU by rapid granular media, and removal to this level should also substantially reduce levels of other pathogenic organisms and toxic particulate matter. The 0.1 NTU level can be measured and is achievable by most of the common filtration techniques in well-designed and operated public water systems.

TURBIDITY CRITERIA DOCUMENT

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I INTRODUCTION

PURPOSE AND SCOPE OF DOCUMENT

The purpose of this document is to review the available scientific data relating to the use of turbidity as a standard to insure the public health safety of drinking water. The information presented will be considered by the Office of Drinking Water in assessing the validity of the current turbidity regulation and in developing revised regulations.

Although the concept of turbidity as an optical indicator of drinking water quality originated many years ago as a standard for drinking water, its application has been subsequently extended to all types of water. For instance, turbidity data are used in sediment transport studies, as a general indicator of suspended solids and in oceanographic studies for mapping mass water movement, charting shoals, locating fish and algae crops etc. Thus, the general subject of turbidity in water is very broad. For purposes of this document, the material concerned will be related only to drinking water. Where applicable, other aspects may be included to support or supplement available information from the water supply literature.

EVOLUTION OF TURBIDITY AS A DRINKING WATER STANDARD

Water quality can mean different things to different people. Consumers who use water for drinking or cooking purposes would judge their water to be of good quality if it was clear or free from apparent turbidity, color, objectionable taste and odor. However, the microbiologist knows that clear water is of poor quality if it contains disease-causing organisms. The toxicologist knows that aesthetically acceptable clear water is of poor quality if it contains harmful soluble or insoluble materials such as cadmium or asbestos fibers. Early man probably was not aware of microbiological and chemical problems. His drinking and cooking water was carried from the wells or streams in jugs, pots or other containers. Because he knew relatively little about disease, any treatment of water probably had as its objective improvement in the appearance or taste of the water. Ancient historians' brief references to water treatment mentioned boiling, filtering, sedimentation and treatment of the water with salts, clays and coagulating plant materials. Again, their standard for quality was probably clarity and palatability (AWWA, 1971). One of man's earliest recommendations for the purification of water was written in Sanskrit about 2000 B.C. (Place, 1905). It stated that water should be kept in copper vessels and exposed to sunlight then filtered through charcoal. Although this was a crude method of handling water, it had many of the essentials of the modern concept of water purification. The soluble copper from the vessel was toxic to the algae and other organisms, while the sunlight further reduced the bacterial population. Filtering through charcoal removed sediment and adhering organisms and also reduced odors and flavors (Taft, 1965).

The first edition of the Encyclopaedia Britannica in 1771 defined a filter as ". . . a strainer commonly made of bibulous or filtering paper in the form of a funnel, in order to separate the gross particles from water and make it limpid" (Baker, 1949). In limpid water one can see the bottom of a stream clearly. Thus, the practice of making water clear or free of particles was well established by 1771, but the degree of clarity was not measurable (AWWA, 1971). One of the first municipal filtration works was built in Paisley, Scotland about 1804. The water of the muddy River Cart, was clarified by filtration then carted to consumers (Baker, 1949). In 1852 a law was passed in London that all water should be filtered (AWWA, 1971). In the United States there were probably about 20 slow sand water filtration plants in 1900. By 1940, there were 100 slow sand filtration plants and about 2,275 rapid sand filtration plants (AWWA, 1971). Although man has attempted to clarify and purify his drinking water by filtration and other methods since the earliest of recorded times, standards for water quality except for aesthetics were absent in historical documents up through the nineteenth century (AWWA, 1971).

Measurable and enforceable written standards for drinking water are of fairly recent origin. In the United States the first standards for the microbial quality of drinking water used in interstate commerce were promulgated by the U.S. Public Health Service, in 1914 (U.S. Treasury Department, 1914). The microbiological method for analysis was described in Standard Methods of Water Analysis, (APHA, 1912). Revisions or additions to these water quality standards were made in 1925, 1942, 1946, 1962 and 1976. The 1925 revision included drinking and culinary water and contained the first mention of a turbidity limit. The report stated, "Turbidity should not exceed 10 (silica scale) and in general it should not be more than 5" (U.S. Treasury Department, 1925). However, this turbidity limit was not mandatory because the report also stated "in many localities supplies of water are available which do not approach the limits allowed here; and in such cases the best available supply should be used" (U.S. Treasury Department, 1925). The method for analysis of turbidity was given in the 5th edition of Standard Methods of Water Analysis (APHA, 1923). In later revisions of the Drinking Water Standards, including the current edition, the method for analysis specified has remained the same (APHA, 1936, 1946, 1960, 1976). In 1942 the U.S. Public Health Service issued revised drinking water standards. A turbidity limit was set at 10 p.p.m. (silica scale)(U.S. Federal Security Agency, 1943). The same turbidity limit was used in the 1946 revision but the limit was specifically set for filtered water. In the 1962 revision of the standards, the last revision prepared by the U.S. Public Health Service, the turbidity limit was set at 5 units. Collection of samples one or more times per week from representative points within the distribution network was specified. The report stated that the limit was ". . . easily attained during general use by properly designed and operated treatment plants and distribution systems. . . . It should not be implied that these turbidity limits represent acceptable effluent standards for water treatment plants. Such plants should routinely produce water with a turbidity of less than one unit" (U.S. DHEW, 1962). The report also stated: "Although these tests (turbidity, color and odor) do not directly measure the safety of water, they are related to consumer acceptance of the water. The levels of 5 units of turbidity, 15 units of color, and a threshold odor number of 3 are levels at which these characteristics become objectionable to a considerable number of people. Experience has shown that under such circumstances, many people turn to alternate supplies which may be less safe" (U.S. DHEW, 1962).

A number of expressions or units of measurement have been used to quantify turbidity including: parts per million (ppm), silica scale, Jackson candle units (JCU), Jackson Turbidity Units (JTU), Formazin Turbidity Units (FTU), Nephelometric Turbidity Units (NTU) and Turbidity Units (TU). The early turbidity standard was 100 mg/l of 200 mesh Fullers' earth. Diatomaceous earth, kaolin (5 g/l) and natural turbid water have also been used as turbidity standards. The Jackson Candle Turbidimeter became the standard reference instrument in the 7th edition of Standard Methods (APHA, 1933). This prompted an increase in the usage of the terms JCU and JTU. The abandonment of the terms silica scale and parts per million occurred in 1955. In the 13th edition of Standard Methods important changes were made in the measurement of turbidity (APHA, 1971). One change involved the use of the nephelometric method for waters of low turbidity (less than 25 TU) and the other change was the use of Formazin standards. With this change came increased usage of the terms FTU and NTU. There has been criticism of the Formazin turbidity standard because Formazin is a polymer and the formation of polymers is recognized as being a nonreproducible reaction (Freeman, 1974). Recently the polymer styrene divinylbenzene was approved as a turbidity standard in addition to Formazin (Federal Register, 1982). Pijanowski, (1976) suggested that latex spheres be used as a reference material in place of Formazin. The last major revision of the water standards was prepared by the U.S. Environmental Protection Agency (USEPA). The new standards were promulgated December 24, 1975, by publication in the Federal Register (Federal Register, 1975) and they became effective on June 24, 1977 (USEPA, 1976). The new standard for turbidity was described as a Maximum Contaminant Level (MCL) of one turbidity unit. The regulations also provided that the turbidity MCL could exceed 1 TU up to a limit of 5 TU if the purveyor could demonstrate that the increased turbidity did not cause any of the following problems:

1. Interference with disinfection.
2. Prevention of maintenance of effective disinfectant agent throughout the distribution system.
3. Interference with microbiological determinations.

In a statement providing the basis for the new turbidity regulation, 6 studies showing a relationship between turbidity or particles and efficacy of disinfection and other treatment processes for removal of microorganisms and 1 study relating turbidity levels to hepatitis incidence were cited. Other statements in support of the regulation included: 1) the possible chlorine demand of suspended material, 2) relationship of turbidity to nutrients and possible regrowth problems and 3) the relationship of turbidity to taste and odor problems.

The new turbidity regulation was applied only to surface waters and the the standard was changed from 5 TU measured in the distribution system to 1 TU at point of entry of water into the distribution system. It is interesting to note that these regulations were published using the term TU, although the method of turbidity measurement was stated as nephelometric. Subsequently the use of NTU has become predominant.

II TURBIDITY OCCURRENCE AND CHARACTERISTICS

SOURCES

A wide variety of particles are present in natural waters, the types, sizes and number of particles present is dependent on their source. These particles, ranging in size from colloidal dimensions to about 100 um, consist of clay, silt, other finely divided organic and inorganic matter and microorganisms.

In many natural bodies of water, much of the suspended material contributing to the turbidity of the water is made up of soil particles derived from the watershed by erosion. The larger sand and silt fractions consist mainly of inorganic rock and mineral materials. Smaller particles are mainly clay minerals, metal oxides, hydrous metal oxides and soil organic material. The organic particles can be classified further as follows: (NRC, 1977)

1. Organic material associated with soil particles.
2. Organic particles from effluent of sewage treatment.
3. Plant and animal debris.
4. Microorganisms
5. Organic colloids.

The concentration of suspended material present often varies seasonally, with precipitation and spring runoff being major factors. Other seasonal factors include phytoplankton blooms in lakes, iron and manganese precipitation as a result of certain limnological conditions and direct atmospheric deposition to water surfaces. Human activities such as highway construction, logging and farming also can have major effects on the turbidity of raw water. The turbidity of the Ohio River at Cincinnati has varied from 5 to over 500 NTU. Lange et al. (1984) reported that the turbidity of two mountain streams varied from 0.5 to 0.32 NTU. In a study of the precision of turbidity analysis (USEPA, 1979) the U.S. EPA Environmental and Support Laboratory (EMSL) used surface water samples. The turbidity of these samples varied from 26 to 180 NTU.

Ground water sources usually contain very low levels of suspended particles and often meet the turbidity MCL with no further treatment. Certain groundwaters may contain relatively high levels of humic materials present in the colloidal or dissolved state. In other groundwaters, high levels of reduced iron and manganese salts may become oxidized to insoluble forms upon exposure of the water to oxygen. High levels of turbidity in groundwaters may be indicative of contamination of the groundwater source by surface water that has entered the groundwater through fractured geological formations or in other ways that bypass the normal percolation process. Greenberg, (1983) pointed out that the turbidity MCL applies only to surface water, but ground water also could be turbid from sand and insoluble iron compounds. However, he did not recommend any changes in the turbidity regulations.

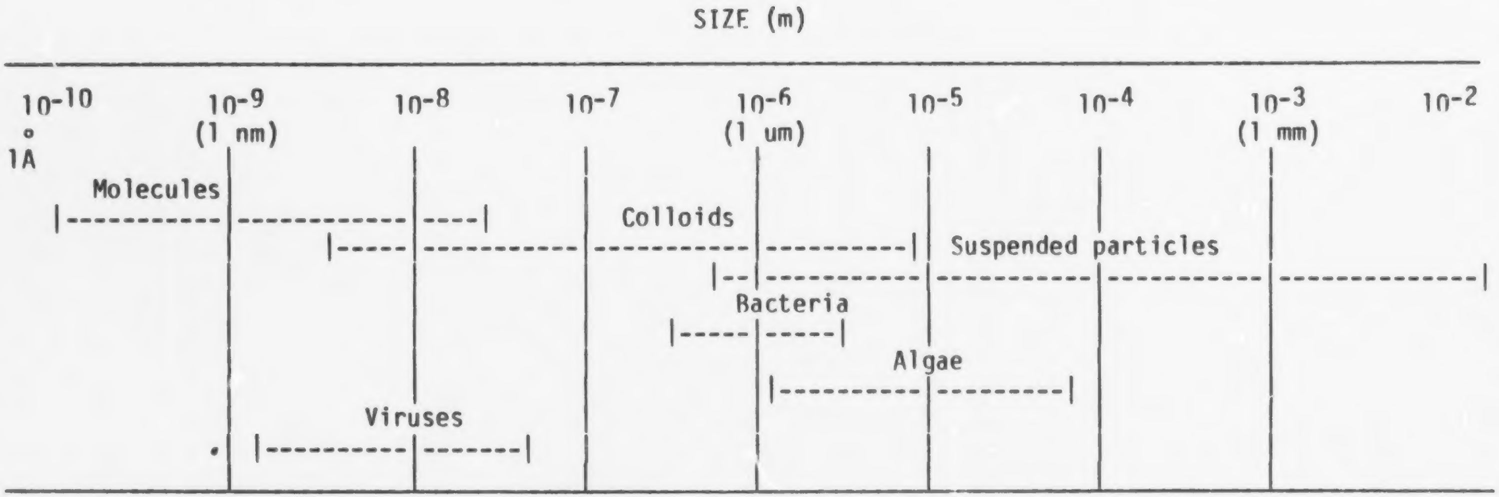
Turbidity in finished drinking water may be present either as a result of lack of treatment, incomplete removal of particles by treatment processes or in some cases as a result of substances added during treatment processes, e.g. coagulant floc, powdered activated carbon, etc., that are incompletely removed in subsequent treatment processes such as filtration. Turbidity also may increase in water within the distribution system as a result of pipe corrosion, growth of microorganisms, or introduction of particulate matter during line repair or through cross-connections or open reservoirs. Turbidity increases also may result from abnormally high flow rates, unusual vibration, or other effects that dislodge particles from pipe surfaces. Under current regulations, turbidity is measured at the point of entry of water into the distribution system. Therefore, turbidity increases occurring within the distribution system are not regulated.

PARTICLE CHARACTERISTICS

The size ranges of various biological and nonbiological waterborne particles are shown in Fig. 1. The particles range in size over 6 or 7 orders of magnitude and consist of a wide variety of materials as indicated above. The consideration of the class of compounds designated as humic acids as particles presents several problems. These particles are very small, falling at the lower end of the range of colloidal particle diameters shown in Fig. 1. A diameter of 5 nm (5×10^{-9} m) usually is used to define the boundary between colloidal materials and true solutions. Black and Christman (1963) estimated the diameter of humic substances to be 3.5 to 10 nm. Schnitzer and Khan (1972) cited a number of studies suggesting humic particle diameters in the range of 6 to 10 nm. Because of this, humic substances often are considered as dissolved materials rather than particles and are included in substances measured as color or apparent color (APHA, 1980). The problem of turbidity interference with the color measurement method is pointed out (APHA, 1980). Because some humic substances do scatter light (Black and Christman, 1963) and therefore are measured as turbidity, they will be considered as particles for purposes of this document.

Size distribution data on particles suspended in fresh and ocean waters and wastewaters indicate that the size frequency distribution can be modeled by a two-parameter power law distribution function based on the number of particles and particle size (Bader, 1970). It is characteristic of all waters that numbers of particles increase as particle size decreases, the coefficient of the power law distribution varying according to the water sampled. The power law model was developed using particle size frequency data based on particles one um in diameter and larger because practical particle counting and sizing methods for smaller particles are not available. How far into the submicrometer range the power law applies is not known.

Relative numbers of particles in various size ranges can have important consequences relative to the significance of turbidity in water. The effects of particle size on available surface area and settling time is shown in Table 1. Settling times would be much longer for less dense particles such as bacteria



From: Stumm (1977)

FIGURE 1 Size Spectrum of Waterborne Particles

and other organic particles. Surface area is an important determinant with regard to surface-related phenomena such as adsorption, and particle aggregation. These physical characteristics are extremely important in considering the role of suspended particles in adsorbing and binding toxic chemicals and other particles such as viruses, bacteria, etc. Larger sized particles may be relatively more important in protecting embedded viruses and other pathogenic microorganisms. The relationship of particle size and number to turbidity measurement is discussed in Section V of this report.

TABLE 1 Relationship of Particle Size to Surface Area and Settling Time

Diam. of Particle, um	Description	Total Surface Area[a]	Time Required to Settle[b]
100	Fine sand	226 cm^2	44 sec.
10	Silt	0.226 m^2	24 min.
1	Bacteria	2.26 m^2	5.1 d.
0.1	Colloidal particles	22.6 m^2	1.4 yr.

a - Area for particles of indicated size produced from a particle 1 cm in diameter.

b - Calculations based on sphere with a specific gravity of 2.65 to settle 30.5 cm (1 ft)

The relative numbers of different types of particles present in a given raw water source is determined by the natural and man related processes and events that contribute the particles. Sources such as erosion on the watershed, agricultural runoff, domestic and industrial waste effluents etc. all contribute various types of particulate matter. In some cases the particle load may be relatively consistent and in other cases it may vary widely depending on the relative loads contributed by individual sources. Obviously, the differences in settling times also are an important determinant of the size distribution of particles remaining in suspension under various hydrological conditions.

The particles that constitute turbidity in water are made up of a wide variety of chemical species ranging from single metal oxides, e.g. iron, to complex organic substances, (e.g. humic acids), and living microorganisms. The chemical composition of the water and the suspended, particles determines particle surface charge which in turn influences chemical reactivity with other particles and dissolved substances. The major physical and chemical factors that influence transfer of materials between water and particles in water are shown in Table 2 (Jennett et al., 1980). Biological factors also play a part in these processes, chiefly by their influences on chemical factors such as pH and eH. Both clays and humic substances are very adsorptive materials. The role of clays and humic substances in complexing both heavy metals and toxic organic compounds is well documented (NRC, 1977; Baker, 1980a; Morton and Sawyer, 1976). In fact, there is a growing realization that most pollutants in water are particles or are associated with particles and that removal of particles by water and wastewater treatment processes can be expected to have major effects on water quality (O'Melia, 1980).

TABLE 2 Factors Influencing the Transfer of Materials Between Water and Sediments

Physical	Chemical
Temperature	Acid-base (pH)
Hydrodynamics and mixing	Complexation
	Oxidation-reduction (eH)
	Sorption-desorption
	Precipitation-dissolution

From: Jennett *et al*. (1980)

Turbidity measurement is used to determine the degree of removal of this wide variety of contaminants by various sedimentation and filtration water treatment processes. Consequently, these removal steps are directed toward greatest turbidity reduction rather than removal of specific types of particles. There also is evidence that conditions for greatest removal of all types of particles by water treatment processes are not the same. For example, the data shown in Table 3 indicate that conditions for best removal of particles by coagulation with aluminum sulfate can vary depending on the nature of the suspended particles. It would appear that coagulant doses and pH conditions selected for maximum removal of hydrophobic colloids such as clays may not

TABLE 3 Characteristics of Coagulation of Dilute Clay Suspensions and Humic Substances with Aluminum Sulphate

Dilute Clay Suspensions	Humic Substances
Optimum pH 6.5 - 7.5	Optimum pH 5-6
Minimum residual turbidity independent of pH	Minimum residual colour dependent on pH
Increased concentration slightly reduces coagulant dose	Increased concentration increases coagulant dose
Dose and optimum pH changed in presence of humic substance	Dose and optimum pH independent of presence of clay

From: Hall and Packham (1965)

produce maximum removal of humic substances (hydrophilic colloids). Sproul (1980) in reviewing the literature on virus removal by coagulation pointed out that certain data indicate that coagulation dosages that produced maximum turbidity removal were not always the most appropriate for removal of viruses (also hydrophilic colloids) although high levels of virus removal were attained.

COMPLIANCE

Violations of the national turbidity standard for turbidity in drinking water are shown in Table 4. These data are for FY 82 and only pertain to community water systems using surface water. Only 3.6 percent of the systems reported violations. Of these, only 1.37 percent were persistent violators, i.e., were in violation four or more months or more than one quarter. For systems which serve 25-500 people, only 3.98 percent reported any violations of the turbidity standard. Thus, for community water systems, the current turbidity standard has been attainable without much difficulty.

Monitoring and reporting violations occurred in 13.68 percent of all systems. The percentage of monitoring and reporting violations was much higher in the smaller systems reflecting the overall lack of operational control often seen in these systems. No data are available on the relationships of these deficiencies to incidence of waterborne outbreaks in community systems.

SUMMARY

The particles that constitute turbidity in water are derived from many different sources and include a wide variety of substances including eroded inorganic rock and mineral materials and organic materials consisting of animal and plant debris, wastewater effluent solids, microorganisms, and organic colloids. Turbidity in finished drinking water may result either from incomplete removal of particles or from particles added or formed during treatment such as activated carbon or coagulant floc. Turbidity may increase in the distribution system as a result of various chemical and biological processes. Sizes of particles measured as turbidity range over 6-7 orders of magnitude. Size distribution of particles is important relative to their significance in adsorption of dissolved contaminants and in the efficiency of removal by various water treatment processes. While water treatment processes are designed for maximum turbidity removal, the conditions employed are not optimal for all types of particles. This is important because certain particles such as pathogens and asbestos fibers have much more human health significance than other particles such as clay minerals.

TABLE 4. Turbidity Violations by System Size Category (FY 82)

Type of Violation	Community Systems Size Category (Population Served)	No. of Systems	No. of Violations					
			Persistent[a]		Intermittent[b]		Total	
			No.	%	No.	%	No.	%
MCL	Very Small (25-500)	3,915	65	1.66	91	2.32	156	3.98
	Small (501-3300)	3,800	48	1.26	100	2.63	148	3.89
	Medium (3301-10,000)	1,678	18	1.07	28	1.67	46	2.74
	Large (10,001-100,000)	1,552	21	1.35	23	1.48	44	2.84
	Very Large (> 100,000)	217	1	0.46	7	3.23	8	3.69
	Total	11,162	153	1.37	249	2.23	402	3.60
Monitoring & Reporting	Very Small (25-500)	3,915	928	23.70	87	2.22	1,015	25.93
	Small (501-3300)	3,800	169	4.45	180	4.74	349	9.18
	Medium (3301-10,000)	1,678	31	1.85	71	4.23	102	6.08
	Large (10,001-100,000)	1,552	9	0.58	46	2.96	55	3.54
	Very Large (> 100,000)	217	0	0.00	6	2.76	6	2.76
	Total	11,162	1,137	10.19	390	3.49	1,527	13.68

[a] 4 or more months or > 1 quarter in violation
[b] 3 or fewer months or 1 quarter in violation

From: U.S. Environmental Protection Agency (1983)

III HEALTH EFFECTS

The possible deleterious effects of particulate matter suspended in drinking water, including both direct effects of particles and indirect effects involving their serving as adsorption sites for toxic chemicals and microbial relationships, was comprehensively reviewed in the 1977 report of the National Academy of Science Safe Drinking Water Committee (NRC, 1977). The Committee concluded that there was no evidence that the two main classes of inanimate particles, clays and organic colloids, have any direct effect on human health. The Committee recommended additional research on the possible direct harmful effects of ingestion of one class of particles, asbestos mineral fibers, including experimental ingestion studies with various sizes of mineral fibers and epidemiological studies in areas that have high concentration of mineral fibers in drinking water. Microorganisms were not addressed as a class of particles in the report but were discussed with regard to their relationship to other particles in water.

The Committee also considered the possible indirect effects of particles in water. The report included an extensive review of the potential of clays and other suspended solids to serve as vehicles for concentration, transport and release of inorganic, organic and biological toxic pollutants. The committee concluded that clays and organic particles have large surface areas and strongly sorb ions, polar and nonpolar molecules and biological agents and that they may exert important health effects through adsorption, transport and release of inorganic and organic toxicants, bacteria and viruses. Such particle-toxicant complexes could be formed either by pollution of soil prior to its being eroded into a stream or by adsorption of toxicants from a stream containing such pollutants. In the adsorbed state such toxicants might be less active. However, it is possible that such toxicants could be released from the particles in the alimentary tract and then exert their toxic effects.

In this section, the potential health effects of particles in drinking water will be discussed in terms of direct and indirect effects, with the emphasis on the more recent literature.

DIRECT CHEMICAL HEALTH EFFECTS

As indicated above, fibrous asbestos particles in drinking water are currently of concern regarding their direct harmful human health effect. The use of turbidity as an indicator of asbestos in water and the relationship of turbidity removal to asbestos particle removal will be discussed under Section IV.

The possible direct toxic effects of humic substances have been considered by a few investigators. Janecek and Chalupa (1969) observed organ degeneration in rats when solid humic acid preparations were added to the diet (50 mg/rat/day). When lesser amounts were fed in drinking water (5-7 mg/day) no strong pathological effect was noted after 19 and 35 weeks. Klocking et al. (1967) reported that humic acids applied to rats intracardially killed 50 percent of the animals at doses of 1127 mg/kg. Visser (1973) demonstrated that humic acids were absorbed through the gastrointestinal tract and were rapidly metabolized, with the liver playing a major role. Visser also reported that the presence of humic acids accelerated the rate of uptake and transport of inorganic ions through the intestinal wall, especially biologically significant high atomic weight metals (zinc, iron, manganese). In contrast, absorption of organic compounds generally was retarded. Janecek and Chalupa (1969) and Visser (1973) also cited studies indicating that humic acid has been used medicinally for treatment of gastropathological conditions, hyperacidity, inflammation of veins and ulcers because of its buffering capacity, bactericidal activity and astringent action.

DIRECT MICROBIOLOGICAL HEALTH EFFECTS

Microorganisms, the other group of particles having potential direct health effects, represent an extremely small portion of the total number of particles in water and those of direct health significance are only a small, but extremely important, fraction of the total microbial population. Their importance is pointed up in a recent review (Akin, 1983) indicating that the infective dose for some isolates of all three types of pathogens (viruses, bacteria, protozoa) responsible for waterborne outbreaks can be extremely low, on the order of 10 or fewer infective units. They constitute a very diverse group with regard to size and biological characteristics. Some characteristics of various types of microrganisms that have been responsible for waterborne disease outbreaks are shown in Table 5. The viruses are very small and are strict parasites, relying on specific living host cells for their replication. The bacteria are more than 10 fold larger in diameter and are capable of living and reproducing independent of a living host. The pathogenic protozoa are approximately an order of magnitude larger than the bacteria. They have a complex life cycle, requiring a living host for completion of a portion of the life cycle and exist outside the host in an inactive resistant cyst form. The size range of these extremely important particles covers nearly three orders of magnitude, lying approximately midway in the six to seven orders of magnitude range of particle sizes in water.

It is significant that we do not rely entirely on removal processes for elimination of this group of particles (pathogenic microorganisms) but rather on disinfection as a final step for inactivation of the remaining pathogens that are not removed by other treatment processes. The available evidence indicates that conventional disinfection, properly applied, is capable of destroying the infectivity of freely suspended, unshielded pathogenic microorganisms, (Hoff and Geldreich, 1981; Hoff and Geldreich, 1982), with the possible exception of cysts of the pathogenic protozoons, *Endamoeba histolytica* (Snow, 1956), and *Giardia lamblia* (Jarroll *et al.*, 1981; Rice and Hoff, 1982). Because of the relatively high resistance to inactivation of *E. histolytica* and *G. lamblia*, longer exposure times and/or higher disinfectant concentrations are required, and removal processes are very important in the control of these pathogens. The relationship between turbidity reduction and removal of these and other pathogens will be discussed under Section IV.

Table 5. Physical Characteristics of Waterborne Pathogens

Type of Pathogen	Shape	Size (um)	Specific Examples	Nature of Surface
Enteric Viruses	spher.	0.02-0.07 (diam.)	Hepatitis A Virus Norwalk Agent Gastroenteritis virus(es)	protein
Enteric Bacteria	cylind.	0.3-0.5 x 2-4	*Salmonella*, *Shigella*, *Escherichia*, *Campylobacter*	lipopolysaccharide, lipoprotein
Enteric Protozoa (cyst form)	ovoid	5-8 x 10-20	*Giardia* *Entamoeba*	mucopolysaccharide?

INDIRECT CHEMICAL HEALTH EFFECTS

As indicated previously, two groups of inanimate particles, clays and colloidal organic particles are important as sorbents of toxic inorganic and organic substances from water. Of the two groups, organic particles are more important as sorbents for nonpolar organic compounds (Schwarzenbach and Westall, 1981). The toxicological effects of contaminant-sediment complexes on benthic and epibenthic organisms have received considerable attention in recent years. The major part of this research has been conducted in marine environments and in situations where concentrations of toxicants have been very high. Little research has been conducted on the potential human health effects of such substances at the low levels present in drinking water.

INDIRECT MICROBIOLOGICAL HEALTH EFFECTS

The major concern about the presence of particles in water and the basis for establishment of a turbidity limit has been the protective effects such particles might offer pathogenic microorganisms from disinfectants used in water treatment.

With few exceptions, the microorganisms of health significance in drinking water all reproduce in the intestinal tract of humans or other animals and are excreted along with feces. Because specific methods by which these microorganisms reproduce differ, their manner of association with each other and with fecal particulate matter may differ. As indicated, viruses reproduce inside living cells initially infected by one or a few virions. They are produced in large numbers and many may remain associated with the cell debris of the cells which replicated them. Some of the viruses excreted may be present in very large aggregates intimately associated with cellular material and other fecal material. Some of these clumps may be broken up during passage through the intestinal tract and by various processes subsequent to excretion.

Enteric pathogenic bacteria are associated less intimately with cells in the intestinal tract. They may or may not invade cells in the course of gastroenteric disease. *Giardia lamblia* and *Entamoeba histolytica* trophozoites are usually confined to surfaces of cells lining the intestinal tract. The conversion of trophozoites to the cyst form apparently occurs in the lower part of the large intestine prior to excretion. Because of differences in size with consequent differences in surface area to mass ratios, smaller particles such as enteric viruses are much more affected by surface charges such as electrical double layer and van der Waals forces than larger microorganisms. Thus, viruses freely suspended in water are more likely to absorb to other suspended particles than are protozoan cysts.

For disinfection to be effective, there must be contact between the agent and the organisms that the disinfectant is to kill. Some of the particles that constitute part of the turbidity consist of particle-microorganism complexes in which a microorganism is adsorbed onto a larger particle. In other cases one or more smaller particles may be adsorbed onto a microorganism or a particle may completely encase a microorganism. In each of these cases varying degrees of protection of the microorganism from the disinfectant can be expected.

Several characteristics of these groups of microorganisms must be considered relative to possible effects of turbidity on their inactivation. One of these is size. As previously indicated, the sizes of representatives of these three groups differ by a factor of over 100X (poliovirus 0.03 um diameter, *E. coli* 0.3 x 1-5 um, *E. histolytica* cysts 5 x 20 um). This would indicate that in the case of virus protection by turbidity, contact between the disinfectant and the microorganism could be prevented by much smaller complexes than would be needed for protection of enterobacteria or protozoans. Size also is important in relationship to the significance of surface charge phenomena in causing aggregation or adsorption of particles. These factors become increasingly important as size decreases, especially for particles in the size range of enteroviruses. Another factor of importance is the relative innate disinfection resistance of the microorganisms themselves. In general, the enterobacteria are the most sensitive to disinfectants, followed by the enteroviruses, while the protozoans exhibit the greatest resistance.

Based on these factors, several assumptions regarding turbidity effects on disinfection efficiency can be made. To protect an enterovirus from disinfectant action, a particle must be larger than 0.03 um in diameter. This size limitation is applicable, whether produced by adsorption of many extremely small particles onto one virus particle or from fragmentation of fecal or other material to form small particles some of which may completely enclose a virus particle. Particles that will protect bacteria or cysts must be correspondingly larger. Thus, the particles present in water which are of concern because of possible disinfection efficiency effects are those ranging upwards from 0.03 um.

Although the concept that certain particles present in water may protect microorganisms from inactivation by disinfection certainly is logical, little direct evidence of such protection was available until recently. Clarke and Chang (1959) stated that turbidity was responsible for disinfection failure which resulted in the Delhi infectious hepatitis outbreak. An AWWA committee (AWWA, 1969) stated that, "Effective disinfection can be carried out only on water free from suspended material." Culp (1974) stated that for good viral disinfection, turbidities of 0.1 JTU were preferable. Cookson (1974) stated that the ability of disinfection to produce virus-free water depends on removal of turbidity to no more than 1 JTU.

A few studies have provided evidence that the presence of particulate matter interferes with effective inactivation of viruses and bacteria in water. In an early rather crude study, Neefe _et al_. (1947) showed that feces from an infectious hepatitis patient, when _suspended_ in water, caused hepatitis in two of five human volunteers after exposure to a chlorine residual of 1.1 mg/L for 30 minutes. In a similar experiment, when the contaminated water was first coagulated and then filtered before chlorination to the same residual, none of five volunteers contracted hepatitis. It is possible that in the latter experiments the HAV virus was removed by coagulation and filtration. Chang _et al_. (1960) demonstrated that enteric bacteria and enteroviruses ingested _by_ aquatic nematodes were completely protected against high residual chlorine levels (80-90 mg/L) even when more than 90 percent of the nematodes were immobilized. Tracy _et al_. (1966) reported the persistence of coliforms in drinking water which was _highly_ chlorinated. The problem was most severe when turbidities were between 5 and 10 units. They demonstated the presence of crustacea in the water and concluded that the most likely explanation was that the coliforms had been ingested by crustacea and were thus protected from contact with the disinfectant.

In a discussion included as part of a paper by Clarke _et al_. (1964), W. W. Sanderson and S. Kelly of the New York State Health _Department_, Division of Laboratories presented evidence that turbidity interfered with disinfection in a water supply. They studied an impounded water supply receiving no treatment other than chlorination. The concentration of free chlorine residual in samples from household taps after a minimum of 30 minutes contact time varied from 0.1 to 0.5 mg/L and the total chlorine residual was between 0.7 and 1 mg/L. These samples consistently yielded confirmed coliform organisms. Turbidities in these samples varied from 4 to 84 TU's and microscopic examination showed iron rust and plankton to be present. They concluded ". . . coliform bacteria were imbedded in particles of turbidity and were probably never in contact with the active agent. Viruses, being smaller than bacteria, are much more likely to escape the action of chlorine in a natural water. Thus, it would be essential to treat water by coagulation and filtration to nearly zero turbidity if chlorination is to be effective as a viricidal process."

More recently, a number of laboratory and field studies designed to provide additional information on the effects of microbial association with particles on drinking water disinfection efficiency have been completed. Because of the general overall greater concern about virus transmission by drinking water and the apparent greater potential for protection of viruses by association with particulate matter, much of this research has been oriented toward viruses. Laboratory studies on microbial association with solids and its relationship to disinfection efficiency have been largely directed at two different types of association: 1) viruses adsorbed onto surfaces of inorganic materials such as clays or enmeshed in precipitates or flocs and 2) viruses associated with organic materials such as cell debris, fecal material, etc. These will be discussed in detail in the following section.

Viruses and Bacteria Associated with Inorganic Solids

In general, the results of disinfection studies involving viruses adsorbed onto surfaces or associated with flocs showed either no increase in resistance or in some cases the rate of inactivation was slowed somewhat. However, even when inactivation rates were reduced, inactivation proceeded under essentially first order kinetics.

Boardman (1976) reported that inorganic particles including alum floc calcium carbonate and kaolin did not interfere with bacteriophage T7 inactivation by chlorine, but did interfere with the rate of inactivation of poliovirus. Inactivation of poliovirus associated with various types of particles after 10 minutes exposure to chlorine at pH 7 was as follows: virus only, 99.7 percent inactivation; virus and alum, 78.4 percent inactivation; virus and $CaCO_3$, 84.7 percent inactivation. The experiments were conducted at 22.5°C and a residual chlorine level of 0.21 mg/L. The chlorine residual determinations indicated that most of the residual was present as combined rather than free chlorine. Although turbidity was not measured, the concentrations of alum (20 mg/L) and kaolin (50 mg/L) used would have produced turbidities in the range of 1-10 NTU. Boardman postulated that the virus protection was due to extensive virus aggregation enhanced by the presence of particles that served as foci for virus adsorption. Experiments designed to prove this were inconclusive. Boardman also noted that the protective effects were greatest in experimental systems in which formation of particles ($CaCO_3$ & alum floc) occurred in the presence of the virus.

Stagg *et al.* (1977) compared the inactivation by HOCl of bacteriophage MS-2 associated with bentonite clay and of freely suspended MS-2 phage. While both freely suspended and clay associated phages were inactivated rapidly, the rate of inactivation of clay-associated phage was somewhat retarded. At equivalent HOCl concentrations ranging from 0.02 to 0.6 mg/L, the length of time required for equivalent inactivation (99 percent) of clay-associated phages was double that for freely suspended phages. Reaction rates in both cases were essentially first-order. Time required for 99 percent inactivation of freely suspended phage was 10 seconds and for clay associated phage 19 seconds at 0.5 mg HOCl/L at 22°C. Turbidity levels for the experiments were in the range of 2 to 4 Jackson Turbidity Units (JTU).

Results demonstrating the absence of a protective effect of bentonite and aluminum phosphate precipitated in the presence of poliovirus are shown in Fig. 2 and 3 (Hoff, 1978). Boyce *et al.* (1981) reported that poliovirus 1, Coxsackie virus A9 and *Escherichia coli* associated with bentonite clay particles were inactivated by ozone at rates similar to those seen for the same organisms when freely suspended in the absence of bentonite. Their results indicated that bacteriophage f2 associated with clay was inactivated at a slightly lower rate than freely suspended phage. Walsh et al. (1980) also reported that alum floc failed to confer protection against viral inactivation by ozone. All of the ozone studies were conducted at turbidity levels of 1 and 5 NTU and the results were similar at both levels.

Scarpino (1979), performing disinfection studies with chlorine dioxide, also showed a lack of protective effect of bentonite clay at 6.25 NTU on poliovirus 1 inactivation (Fig. 4). At higher temperatures (25°C) a difference occurred in inactivation rates between freely suspended and bentonite adsorbed virus. Concentration vs. time plots of inactivation of freely suspended and bentonite associated virus within a turbidity range of approximately 1-16 NTU at 5°C and 25°C are shown in Fig. 5 and Fig. 6 respectively. It is apparent that at 5°C (Fig. 4) poliovirus associated with bentonite was inactivated at similar rates regardless of the turbidity level and that these rates did not differ from those obtained for freely suspended virus. However, at 25°C (Fig. 6) points representing results of disinfection experiments with bentonite-associated polioviruses are displaced to the right of the curve representing inactivation of freely suspended virus, indicating that the bentonite associated virus was inactivated more slowly. Other experiments conducted at 15°C showed similar differences but to a lesser degree than at 25°C. It is possible that the different effects at the higher temperatures were due to the overall higher rate of inactivation at 25°C (on the order of 4 fold faster than at 5°C). Minor differences due to partial protection of virions by association with bentonite may have been detectable at rapid inactivation rates but not at slower rates. Stagg et al. (1977) reported similar results on inactivation of freely suspended and clay associated MS-2 bacteriophage, which is very sensitive to chlorine. Differences in rates were shown but as with other reported results, disinfection kinetics were essentially first order with clay associated, as well as freely suspended bacteriophage.

Viruses and Bacteria Associated with Organic Solids

Results of disinfection studies on other types of particulate-microorganism complexes present a different picture. Results of studies by Hoff (1978) on inactivation of viruses associated with cell debris and coliforms associated with primary wastewater effluent solids are shown in Fig. 7 and Fig. 8, respectively. In contrast to inactivation curves previously shown, survival of microorganisms associated with these particles departs substantially from first order kinetics. Inactivation rates are characterized by an initial rapid rate which gradually decreases eventually showing little or no further decline. Foster et al. (1980) found that fecal-associated coliforms, poliovirus and porcine enterovirus were protected to some extent from inactivation by ozone. Sproul et al. (1979) reported that poliovirus associated with cell material was highly protected with a portion of the virus being detectable in some experiments after exposure to ozone levels of 2.5-5.0 mg/L for 10 minutes. It should be emphasized that in all of the above experiments the solids with their associated microorganisms were extensively washed free of dissolved disinfectant demand materials by repeated cycles of centrifugation in disinfectant demand-free water. Also, as in the studies previously described, turbidity levels in the experiments were maintained in the range

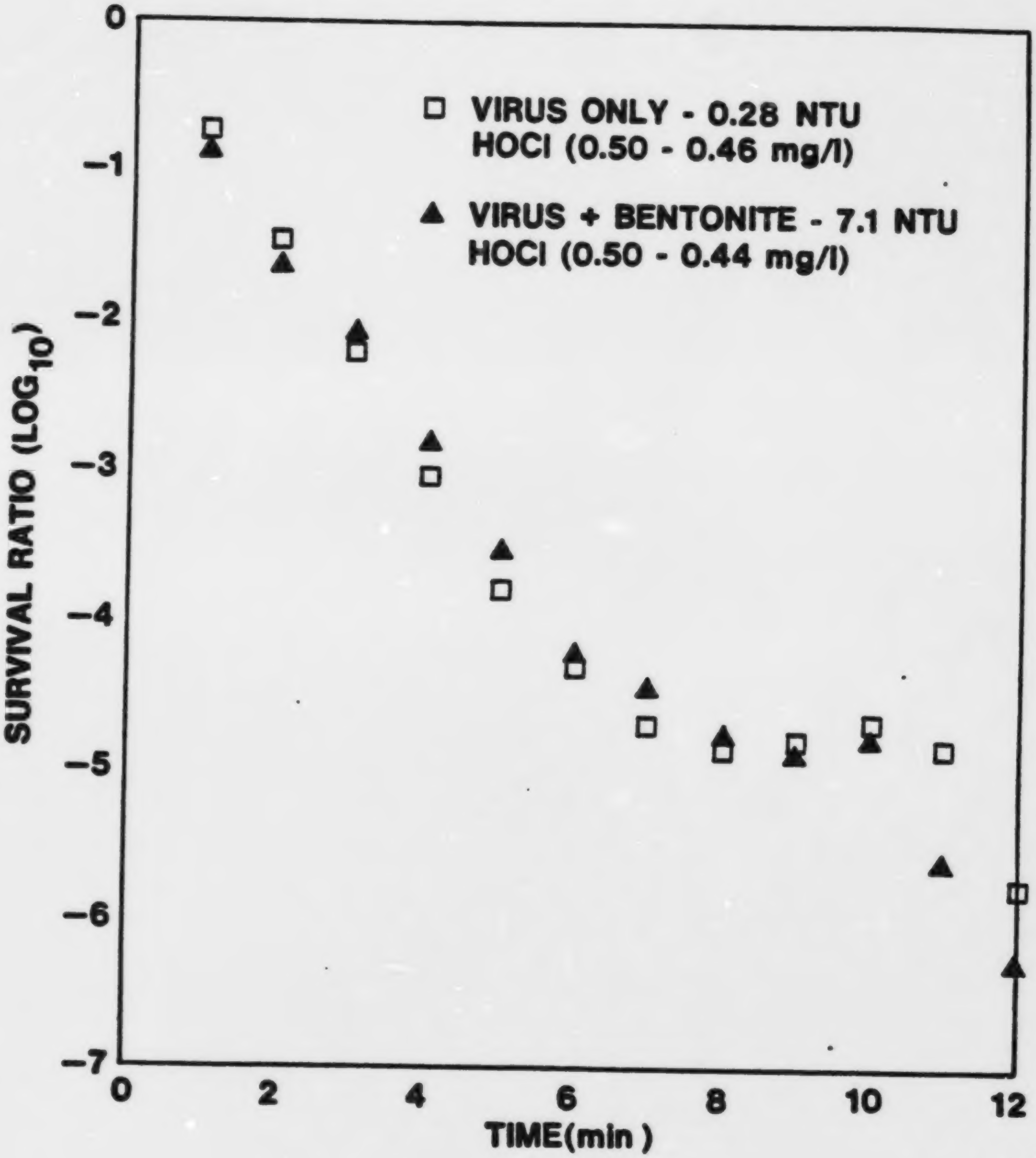


Fig. 2. Inactivation of Bentonite-Associated Poliovirus by Chlorine (pH 6.0, 5°C)

From: Hoff (1978)

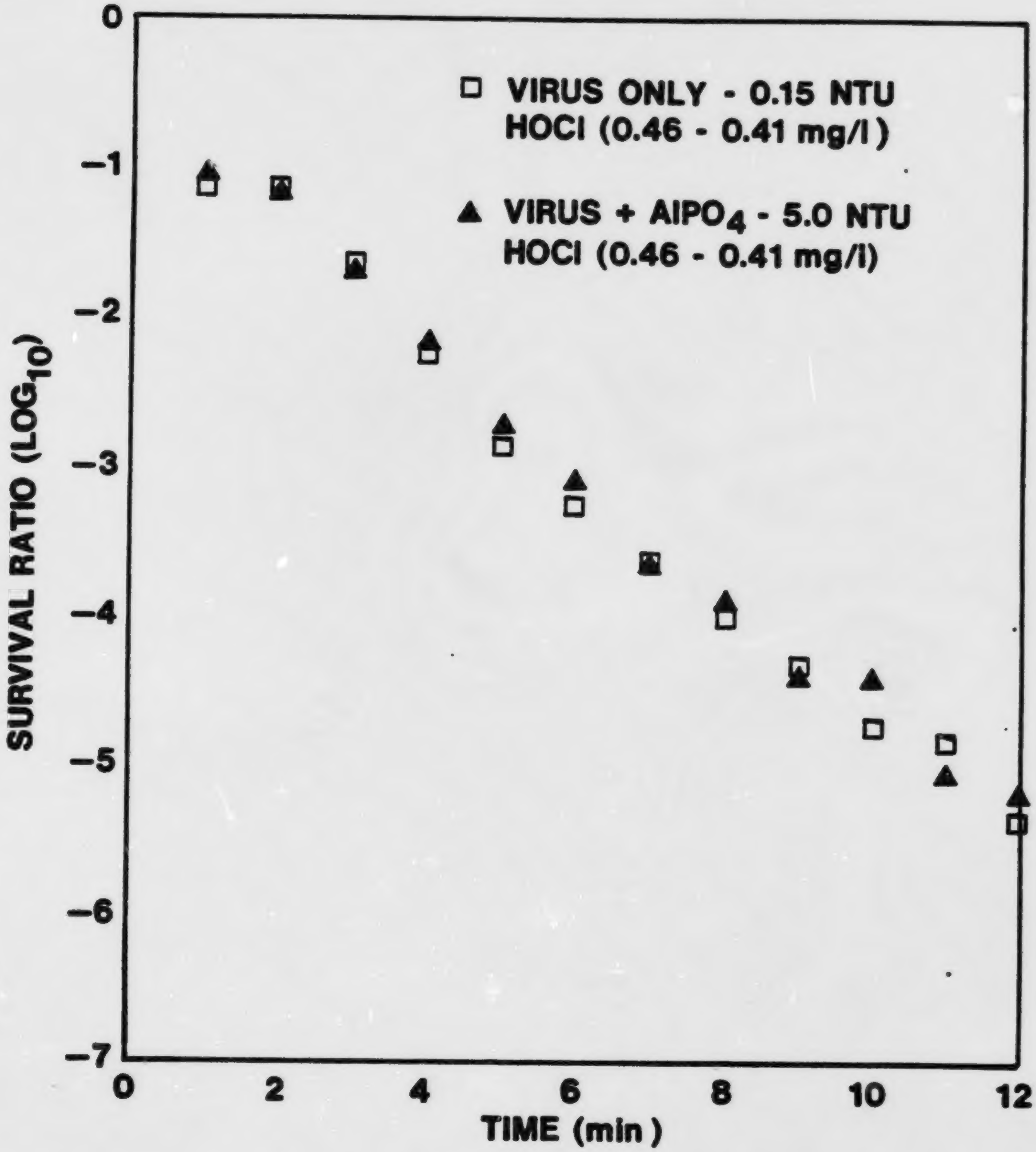


Fig. 3. Inactivation of $AlPO_4$ - Associated Poliovirus 1 by Chlorine (pH 6.0, 5°C)

From: Hoff (1978)

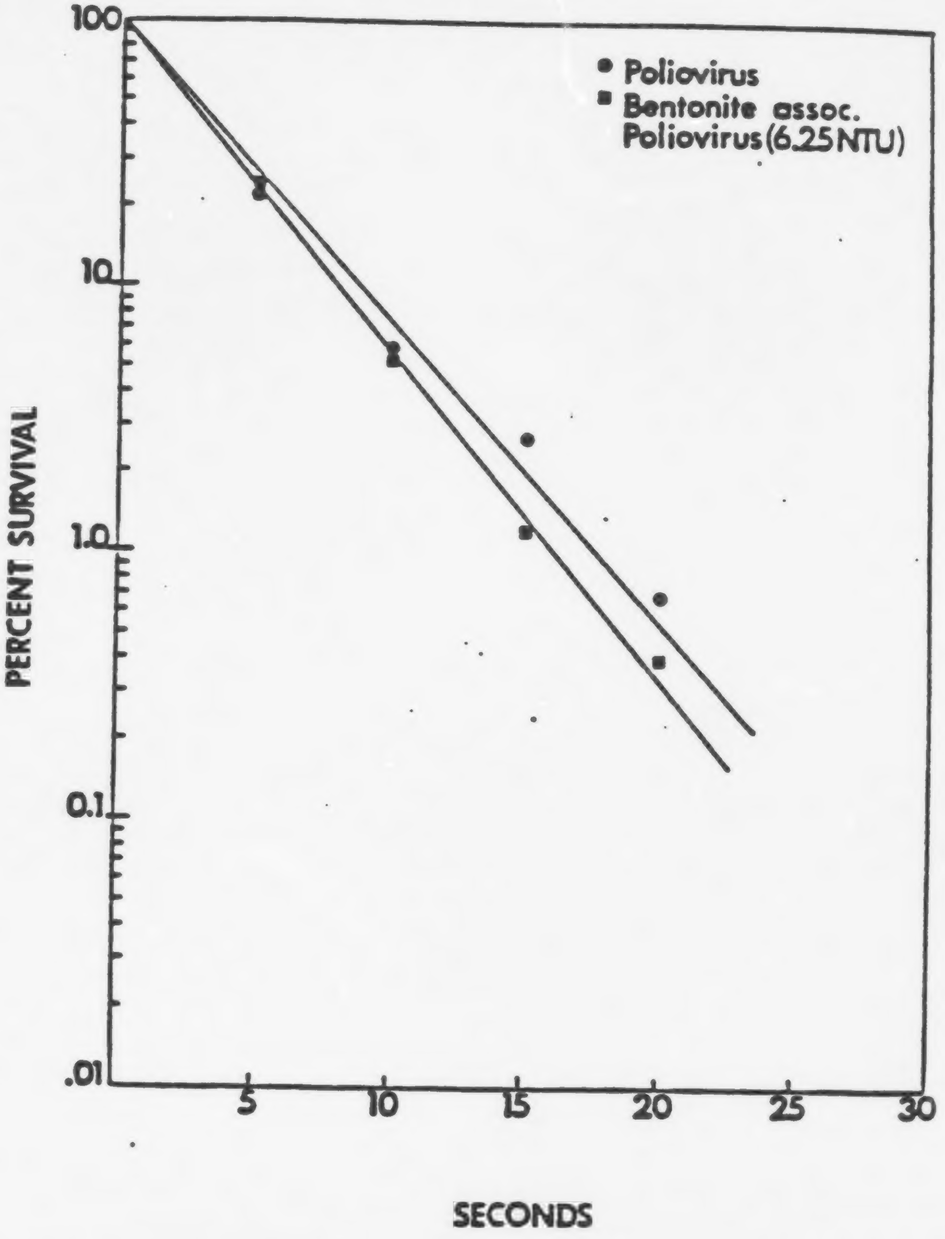


Fig. 4. Survival curve comparison of the inactivation kinetics of poliovirus 1 singles (control) to the polio-bentonite complex at 6.25 NTU at 12.0 mg/l chlorine dioxide using the dynamic apparatus at 5°C at pH7.

From: Scarpino (1979)

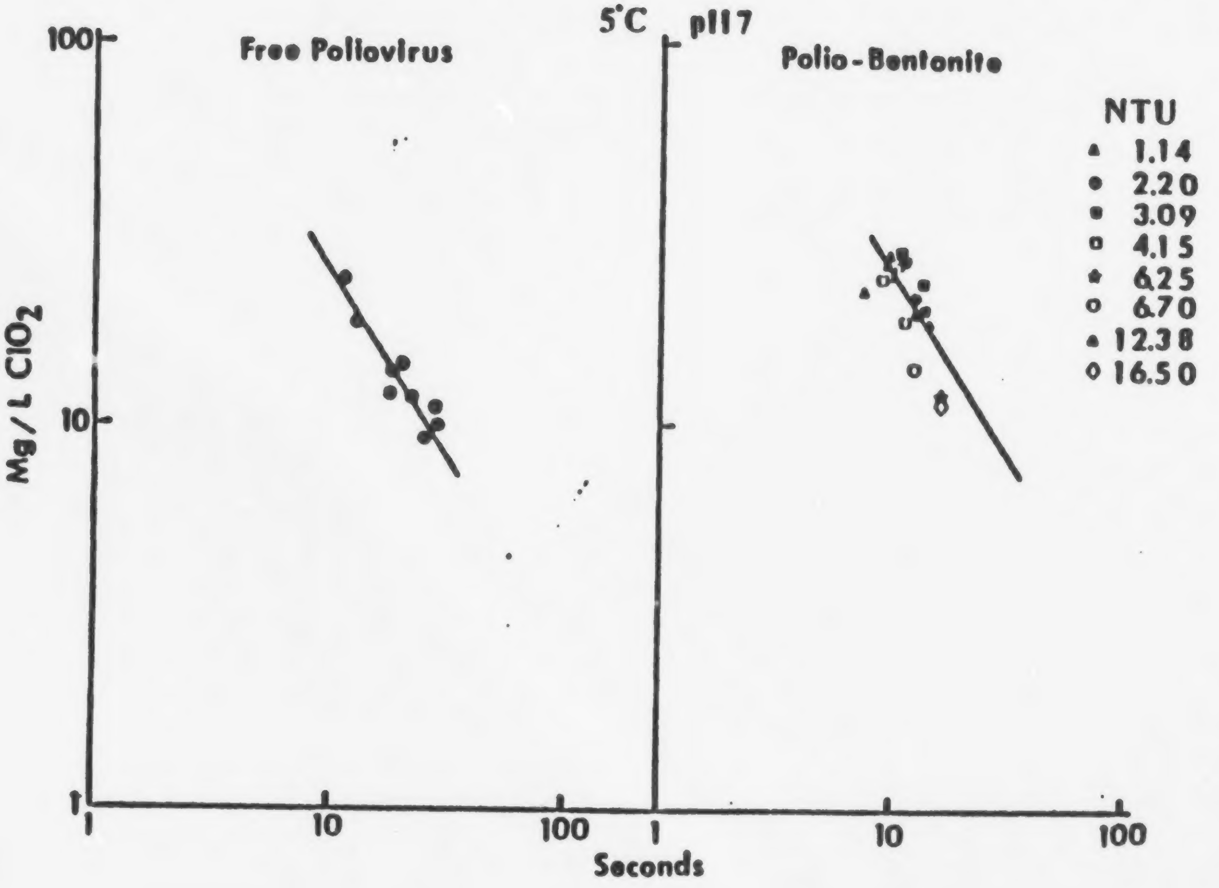


Fig. 5 Concentration-time relationship for 99% inactivation of poliovirus 1 singles and bentonite-adsorbed poliovirus 1 singles at 5°C at pH 7.

From: Scarpino (1979)

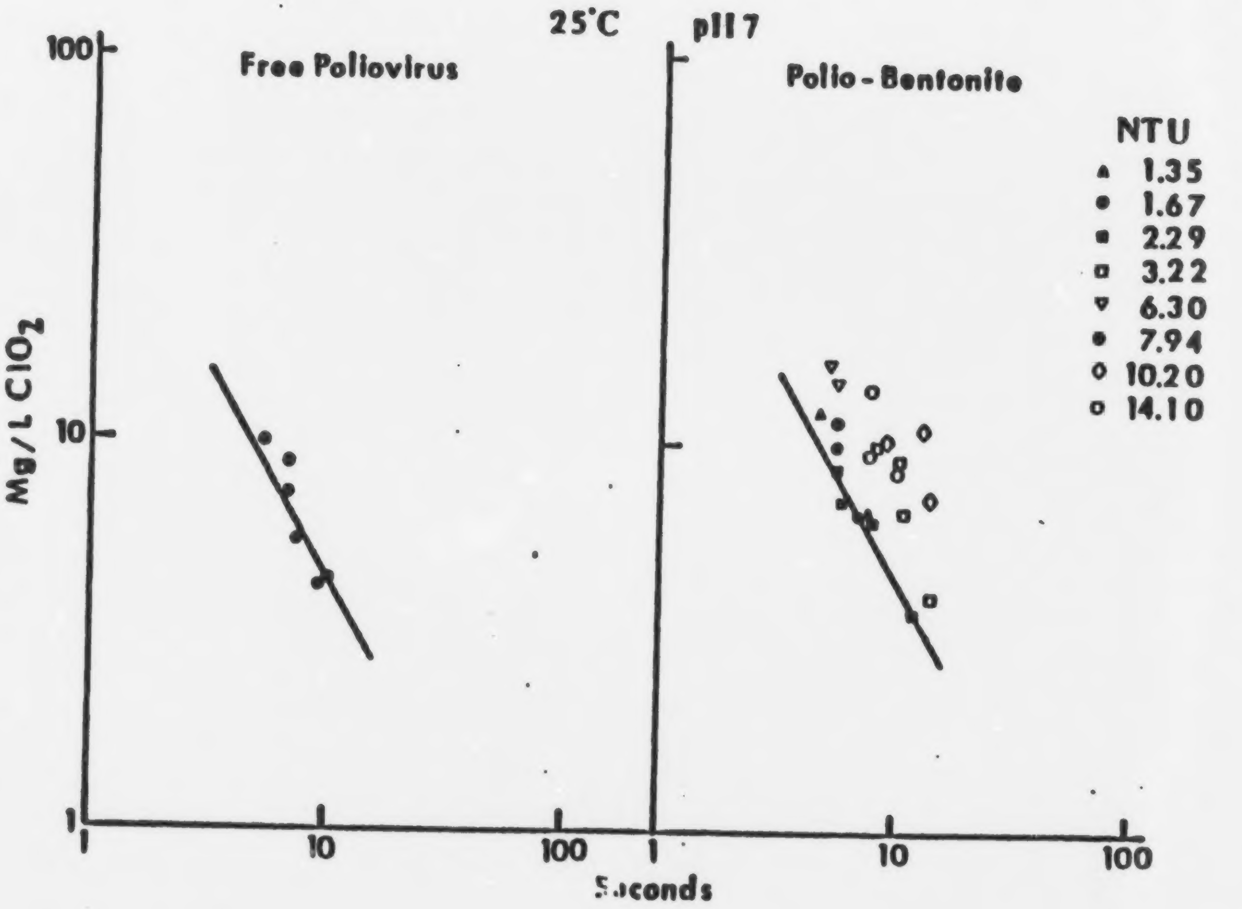


Fig. 6. Concentration-time relationship for 99% inactivation of poliovirus 1 singles and bentonite-adsorbed poliovirus 1 singles at 25°C at pH 7.

From: Scarpino (1979)

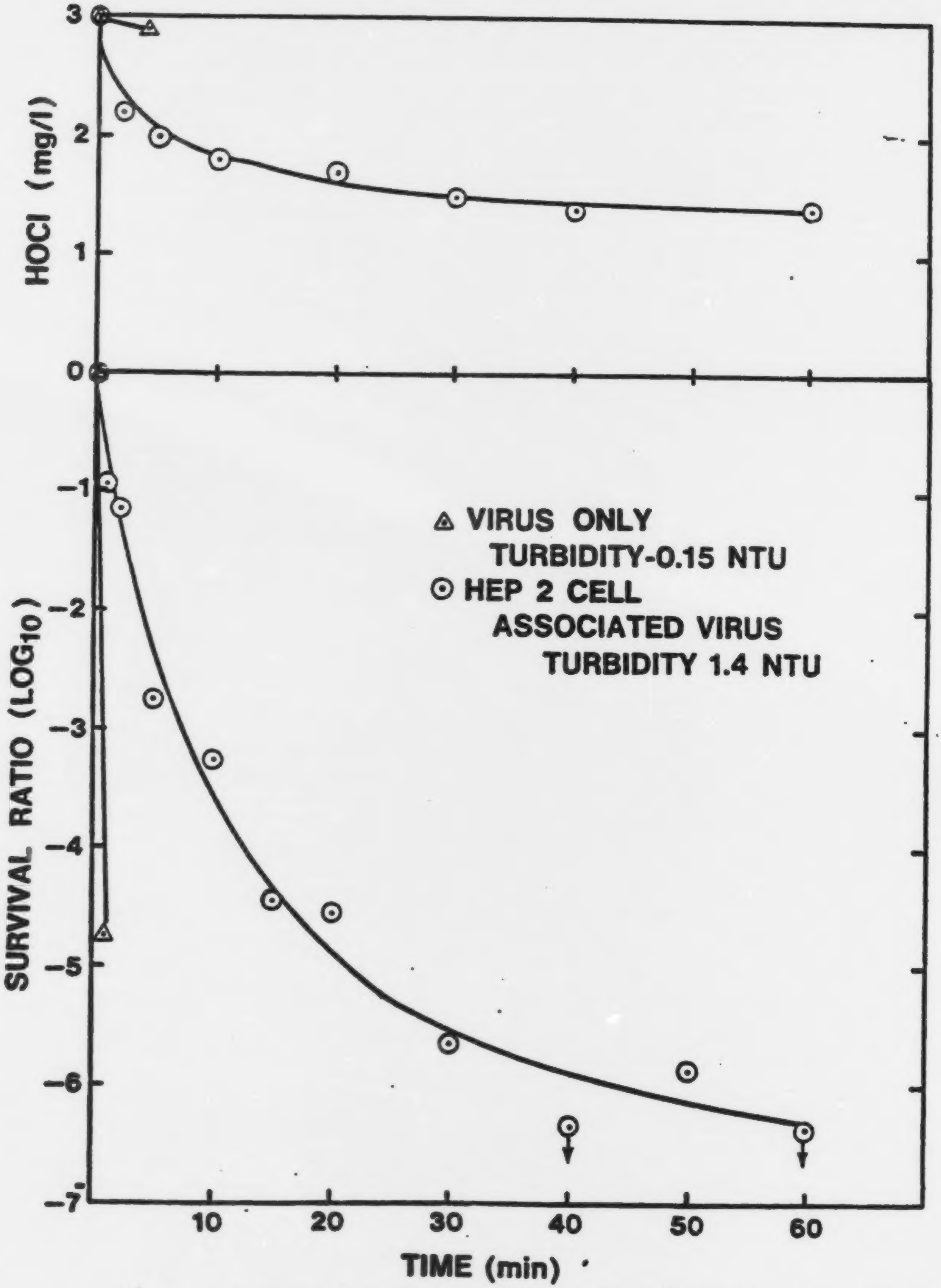


Fig. 7. Inactivation of Cell-Associated Poliovirus by Chlorine (60 min.)

From: Hoff (1978)

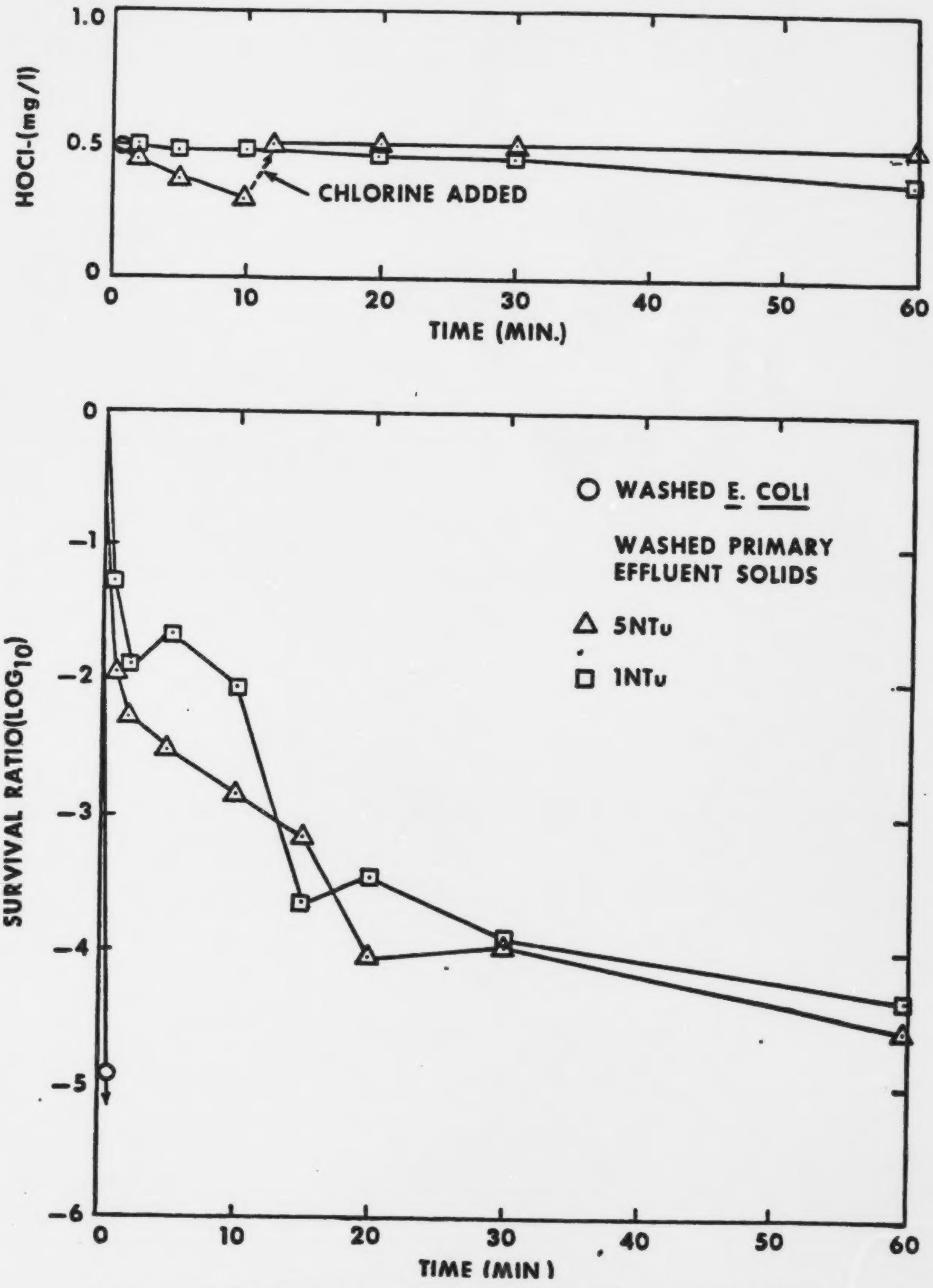


Fig. 8. Inactivation of Coliforms Associated with Primary Effluent Solids by Chlorine (pH 6.0, 5.0°C)
From: Hoff (1978)

of 1 to 5 NTU so that the results would be relevant to the current turbidity MCL. Hejkal et al. (1979) reported that a four-fold increase in chlorine was needed to inactivate feces-associated poliovirus as compared to free or surface adsorbed viruses. Because they did not attempt to remove chlorine demanding substances from the fecal preparations used, the free chlorine added to these preparations was converted to chloramine, a much weaker disinfectant. They reported that the protection afforded by virus occlusion within particles was relatively small compared to the disinfectant demand effects. Scarpino (1979) studied chlorine dioxide inactivation of poliovirus associated with cell debris material. In contrast to similar studies with chlorine (Hoff 1978) and ozone (Foster et al., 1980), the studies with chlorine dioxide indicated virtually a complete lack of protection. Other than the difference in disinfectant used, the only other difference between the studies using chlorine dioxide and those using chlorine and ozone research was the cell line used to prepare the cell debris associated virus. For the chlorine dioxide study the BGM cell line was used whereas in the other two the HEP-2 cell line was used. The significance of this has not been investigated.

Some of the results of additional studies on inactivation of coliforms associated with primary effluent solids are shown in Fig. 9 and 10 (Hoff, unpublished data). In these studies attempts were made to separate primary effluent solids into two size ranges, one group consisting of those particles > 7 um in diameter and the other of those < 7 um in diameter. After separation, each fraction was washed by repeated resuspension and sedimentation in chlorine demand-free water to remove dissolved chlorine demand materials. The results of disinfection studies on these solids consistently show that the coliforms associated with the large size fraction survived exposure to disinfectants to a much greater degree than coliforms associated with the small size fraction (Fig. 9). Treatment of the large size fraction with high speed homogenization prior to disinfection consistently caused a marked decrease in the disinfectant resistance of the associated coliforms (Fig. 10). Initial coliform levels after homogenization frequently increased by 5 fold or more. Results of particle counting and sizing on the small and large fraction and the effect of the homogenization procedure on the large particle fraction are shown in Table 6. It is evident that the separation into large or small size fractions is not clearcut. Results of particle counts performed at various times after separation indicate that the finding of large particles in the small particle fraction is due in part to reagglomeration of some of the small particles after separation. The shift toward higher numbers of smaller particles in the large size fraction after homogenization is evident.

The available data indicate that the proportion of microorganisms associated with solids in fecal material and sewage probably is low. Foster et al. (1980) reported that more than 90 percent of the viruses and coliforms present in fecal specimens were not associated with solids. Wellings et al. (1976) reported that only 17 percent of the viruses in unchlorinated wastewater were solids-associated. This increased to 44 percent in chlorinated effluents, probably due to the greater inactivation of unprotected viruses by the disinfectant. Hejkal et al. (1981) concluded that 97 percent of the viruses in the unchlorinated effluent used in their studies were either free or associated with particles < 0.3 um in diameter. Some particles in the upper end of that size range are on the order of 10 fold larger in diameter

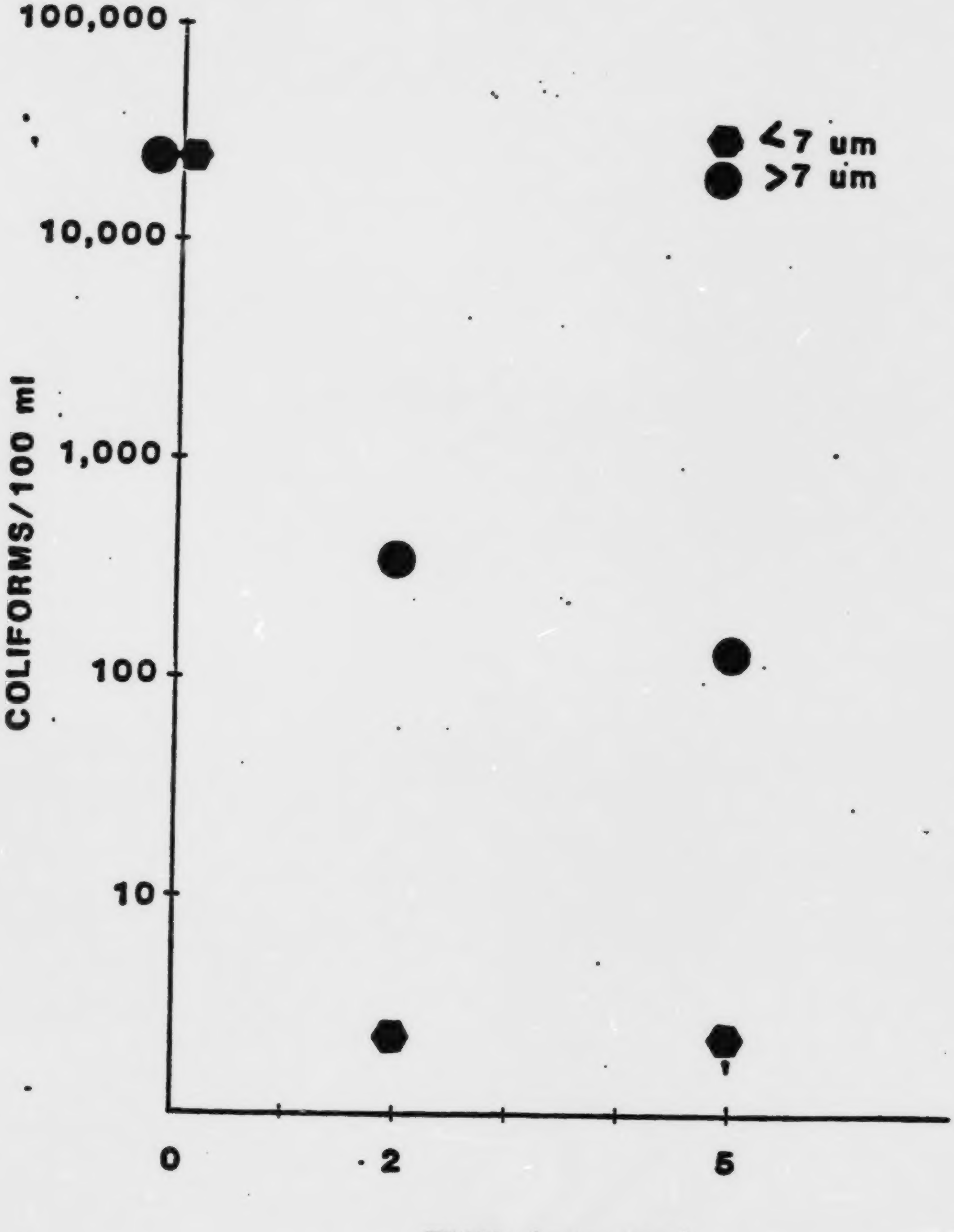


Fig. 9. Effect of Particle Size on Inactivation of Coliforms Associated with Primary Effluent Solids (0.5 mg/L free chlorine, pH 6.0, 5.

From: Hoff (Unpublished data)

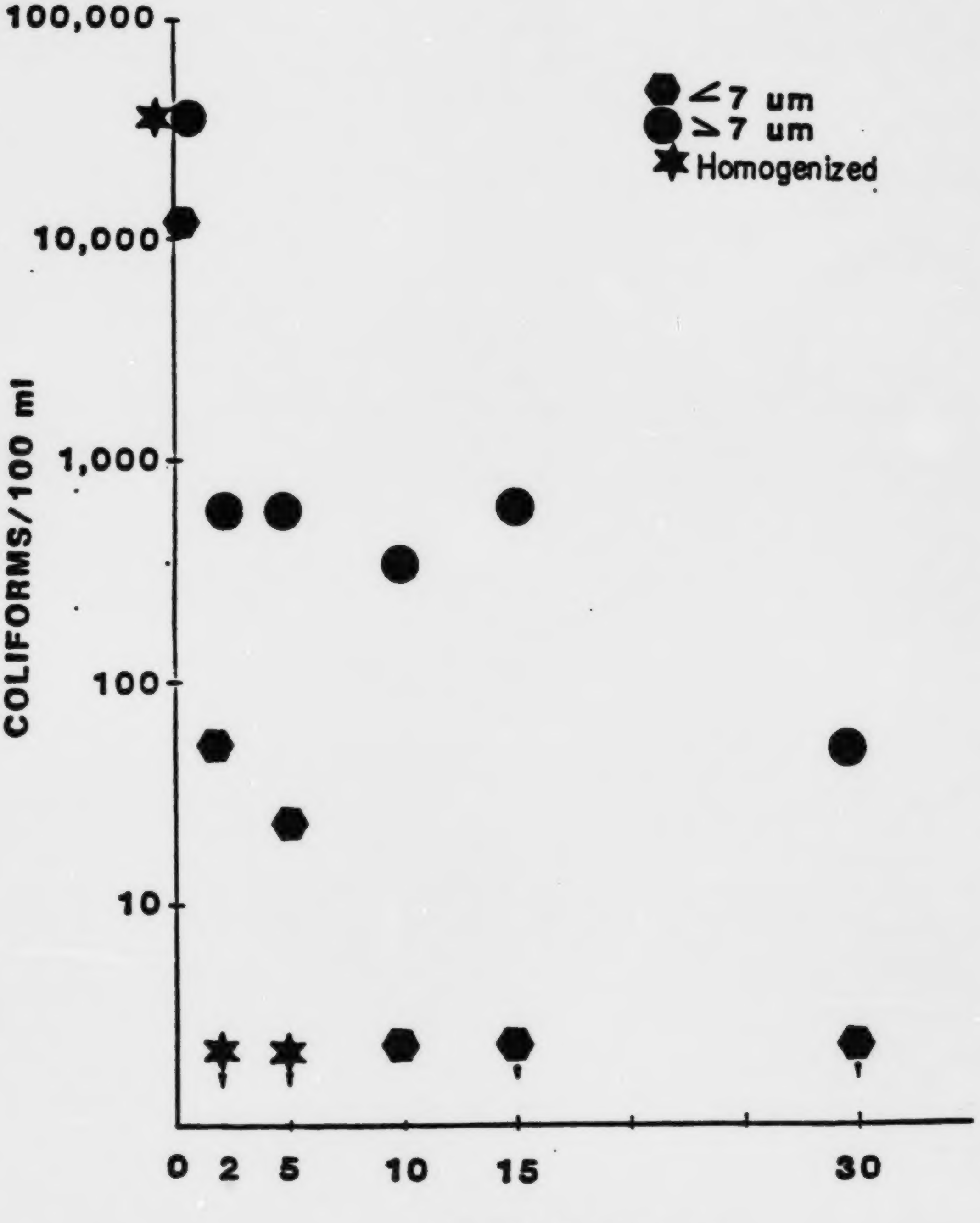


Fig. 10. Effect of Particle Breakup on Inactivation of Coliforms Associated with Primary Effluent Solids (0.5 mg/L free chlorine, pH 6.0, 5.0 C)

From: Hoff (Unpublished data).

Table 6. Particle Counts of Effluent Solids Fractions

Particle Diameter Range (um)	Particle Fraction		
	< 7 um	>7 um	> 7 um[a]
3.5-5	454[b]	911	2,384
5-7	118	563	990
7-9	74	420	663
9-12	44	372	384
12-15	19	235	202
15-20	32	283	160
20-30	16	235	70
30-50	4	103	18

[a] After homogenization (Virtis, setting 40, 2 min)
[b] Number of particles/mL

Hoff (Unpublished data)

than polio virions and it is likely that some of them could offer a substantial degree of protection to embedded virions. On the other hand particles in this size range (0.3 um) would be too small to occlude larger organisms such as enteric bacteria from contact with a disinfectant.

The manner in which viruses in fecal material are associated with particles is not known. However, recent studies on detection of gastroenteritis virus in feces by electron microscopy provide some information as illustrated by Fig. 11 and 12. Fig. 11 shows a fairly large area with virion groups of various sizes in a variety of associations. Fig. 12 shows a large clump of viruses apparently in association with cell membrane material. Narang and Codd (1981) have shown similar clumps with diameter exceeding 1 um. It is likely that some of the viruses in such clumps would be protected from contact with disinfectant.

The results of these studies indicate that we may expect microbial association with particles to affect disinfection rates in one of three ways. These are illustrated in Fig. 13. Adsorption of microorganisms on surfaces of particles or inclusion in porous floc may either have no effect on disinfection rate (Curve A) or cause some reduction in rate with first order kinetics maintained (Curve B). Microorganisms embedded in particles and thus shielded partially or completely from contact with the disinfectant, can be protected to a high degree. Disinfection rates under these conditions depart

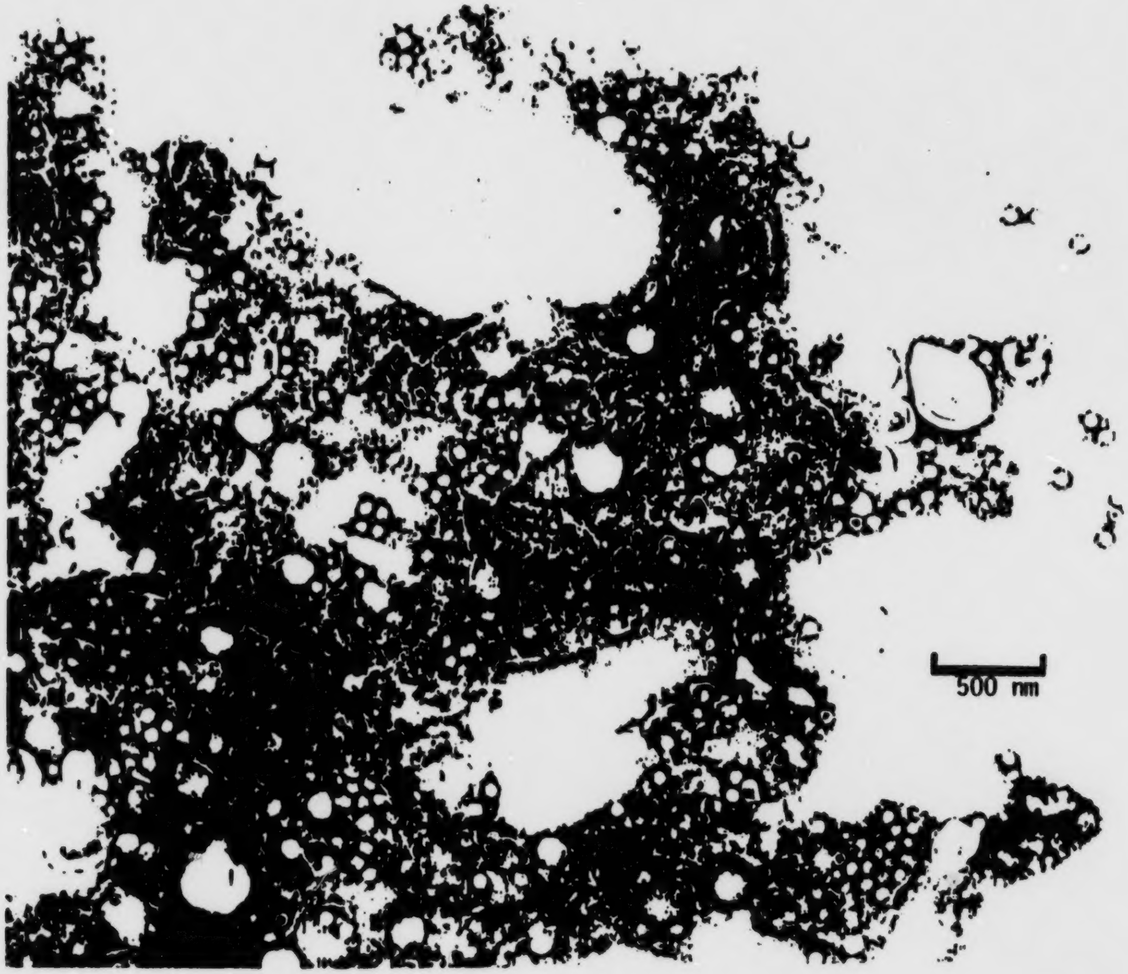


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Fig. 11. Gastroenteritis Virus in Fecal Material (Courtesy of Fred P. Williams)

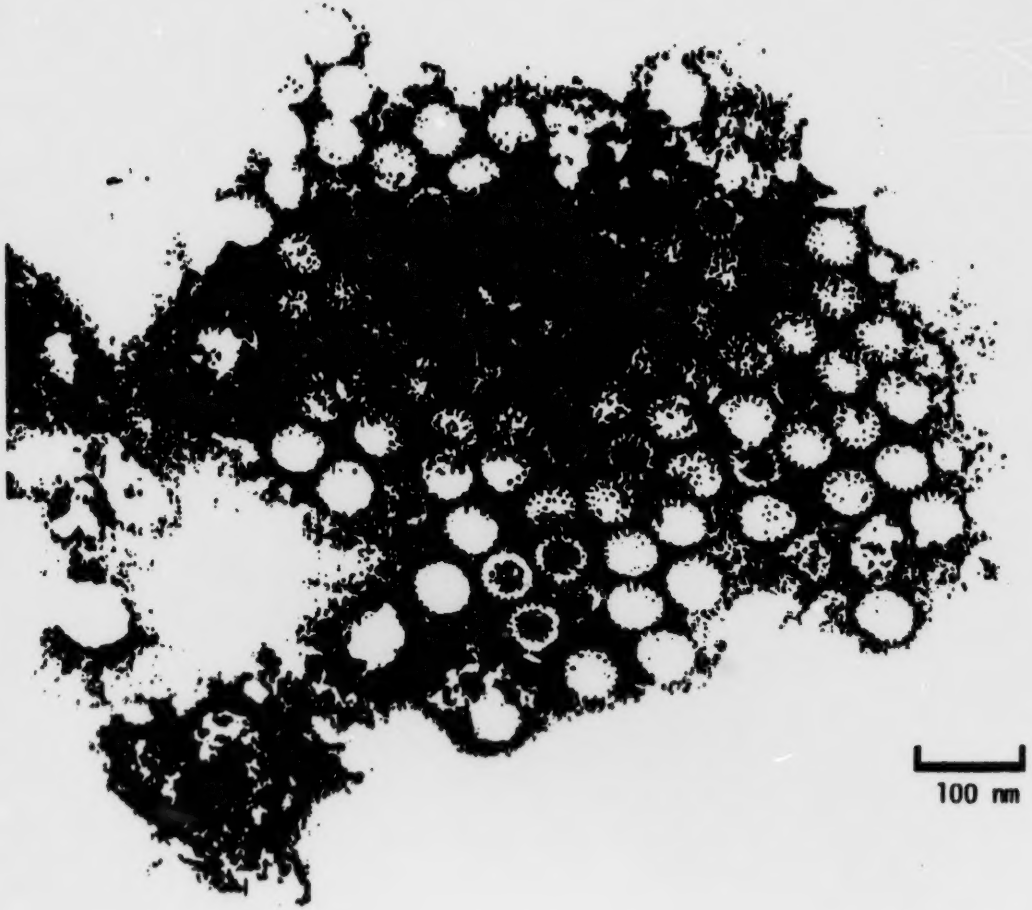

Fig. 12. Large Clump of Gastroenteritis Virus Particles in Fecal Material (Courtesy of Fred P. Williams)

from first order kinetics with a small portion of the microorganisms surviving after long exposure times (Curve C). Significantly, the types of particles that confer protection of the type illustrated by Curves B and C, i.e. flocs, cellular debris, sewage effluent solids, are also those that would most likely contain pathogenic microorganisms.

Field Studies

A number of field observations and studies also are relevant to the indirect relationship of turbidity in drinking water to human health. Logsdon and Lippy (1982) reviewed the literature on the role of filtration in preventing waterborne disease. They cited a number of instances in Europe in the late 1800's and the U.S. in the early 1900's demonstrating that water filtration alone before the advent of drinking water disinfection, resulted in reducing death and illness from cholera, typhoid fever and other waterborne diseases. Dramatic reductions in typhoid fever death rates in Albany, New York (Fig. 14) and Cincinnati, Ohio (Fig. 15) occurred following the installation and use of filtration in drinking water treatment. It is important to note that these major reductions occurred before the later introduction of disinfection as a water treatment unit process. Although no turbidity standards were in effect at that time the data show conclusively that reduction of the amount of particulate matter in water reduced the incidence of waterborne disease.

Lippy and Waltrip (1984) reviewed the 672 waterborne disease outbreaks that occurred betwen 1946 and 1980. The outbreaks were geographically distributed by state and rate-based according to the number of water systems in each state. A comparison was then made between the states with a low outbreak rate and those with a high rate by computing ratios of water systems using treatment (filtration plus disinfection) of surface water as opposed to those using untreated (includes disinfection only) surface water. Comparison of the ratios indicated that States exhibiting a low outbreak rate had a much higher ratio (four to one) of systems providing treatment. They concluded that the comparison reinforces the need for adequate treatment of surface water. Adequate treatment of surface water has historically been defined by regulatory agencies and the water utility industry as including filtration as a treatment process. These findings provide indirect evidence that removal of particles during water treatment is important in preventing waterborne disease outbreaks.

Hudson (1962), in a study of the quality of water produced by various water treatment plants in the U.S., reported a correlation between turbidity levels in finished water and hepatitis incidence in a number of cities. A summary of those data are shown in Table 7. In a discussion section following the paper (Hudson, 1962) caution was urged in overinterpreting the limited data presented. It also was pointed out that infectious hepatitis in the same cities varied considerably in subsequent years although no evidence of changes in water quality was presented. Mosley (1967) reported that calculation of a correlation coefficient for the Hudson (1962) data failed to substantiate the assumed relationship.

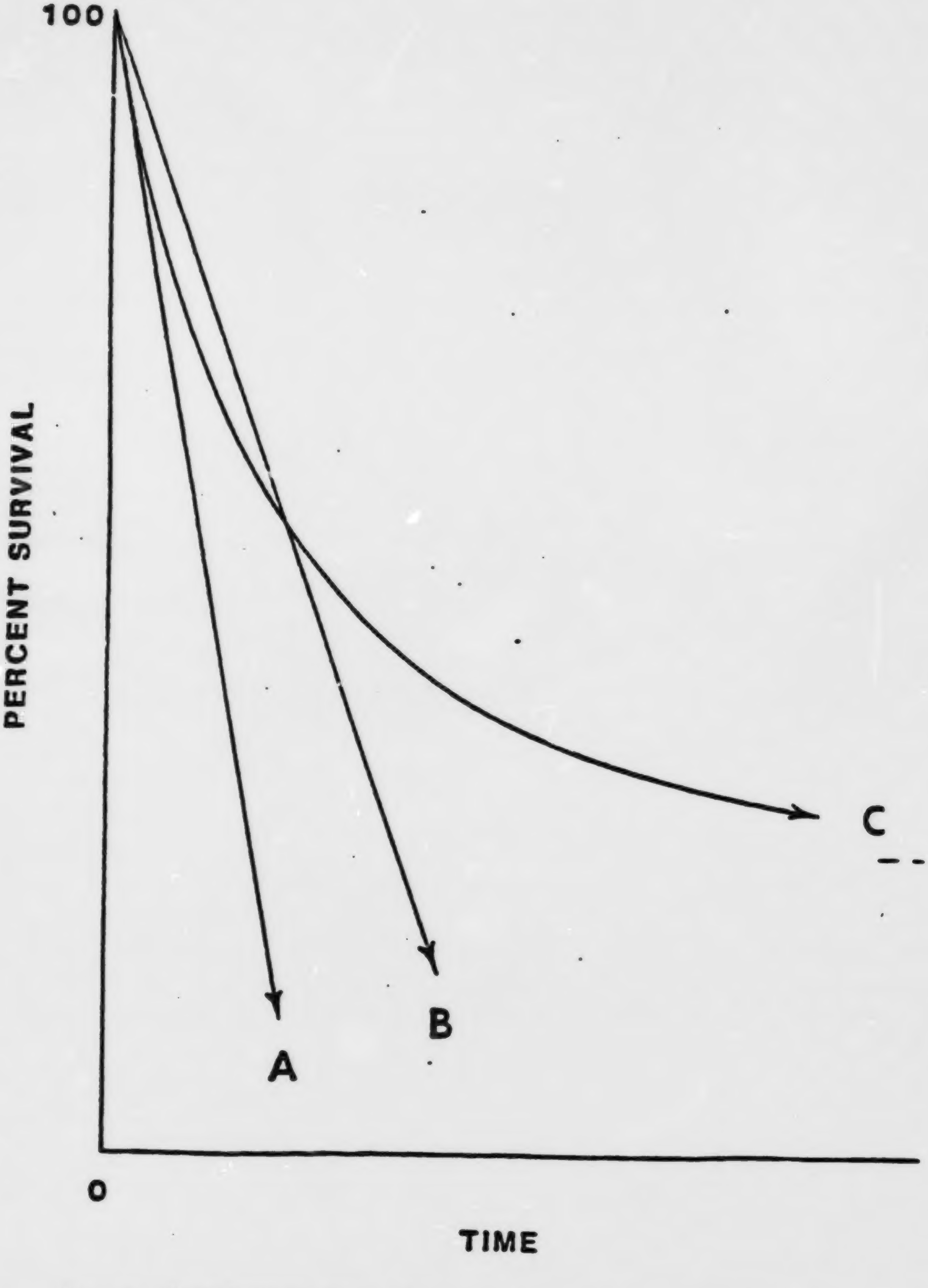

Fig. 13 Disinfection Curves Expected with Different Types of Micro-organism-particle Complexes

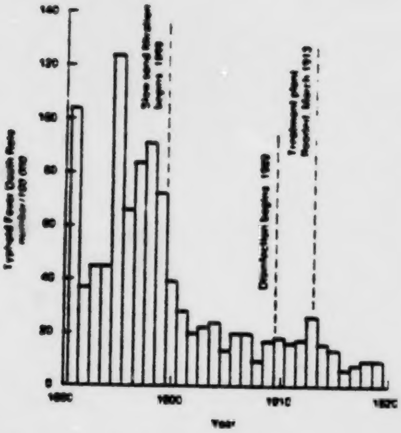

Fig. 14. Reduction of typhoid fever by water treatment at Albany, N.Y.

From: Logsdon and Lippy (1982)
Data from Willcomb (1923)

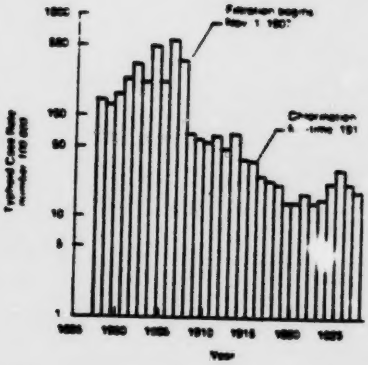

Fig. 15. Effect of Filtration and Chlorination on Incidence of Typhoid Fever in Cincinnati, Ohio, 1895-1930.

From: Logsdon and Lippy (1982)

Table 7. Filtered-Water Quality and Hepatitis Incidence, 1953

City	Average Turbidity TU	Final Chlorine Residual mg/L	Hepatitis cases/100,000 people
G	0.15	0.1	3.0
C	0.10	0.3	4.7
H	0.25	0.3	4.9
B	0.2	-	8.6
M	0.3	0.4	31.0
A	1.0	0.7	130.0

From: Hudson (1962)

In a more recent study, LeChevalier et al. (1981) reported a correlation between coliform disinfection efficiency and turbidity in raw surface waters treated by disinfection only. The results are shown in Fig. 16. The results indicate that coliforms in high turbidity water (13 NTU) were reduced by only about 20 percent of the initial level while in low-turbidity water (1.5 NTU) coliforms were reduced by more than 3 orders of magnitude at substantially lower chlorine doses. They developed a statistical model to predict the impact of turbidity on disinfection efficiency for systems in the Pacific Northwest using chlorination only for treatment of surface waters. They also concluded that turbidity control to at least the 1 and 5 NTU levels is justified in order to maintain adequate drinking water quality.

TURBIDITY EFFECTS ON DISINFECTANT DEMAND

The current turbidity regulation provides that the 1 NTU MCL can be exceeded up to a limit of 5 NTU if it can be shown that the higher turbidity level does not prevent maintenance of effective disinfection throughout the distribution system. The rationale for this provision is the assumption that the turbidity may exert a significant disinfectant demand, thereby depleting the residual present when the finished water enters the distribution system.

Few studies have specifically addressed the basis for this provision. Feben and Taras (1950) studied the chlorine demand of the Detroit, Michigan water supply. They concluded that turbidity was a minor factor in determining chlorine demand. LeChevallier et al. (1981) showed a correlation between turbidity and chlorine demand in raw waters from six watersheds serving as sources for small systems employing chlorination only for treatment. However, chlorine demand studies on samples from which the turbidity had been removed indicated that 90 percent of the chlorine demand was associated with dis-

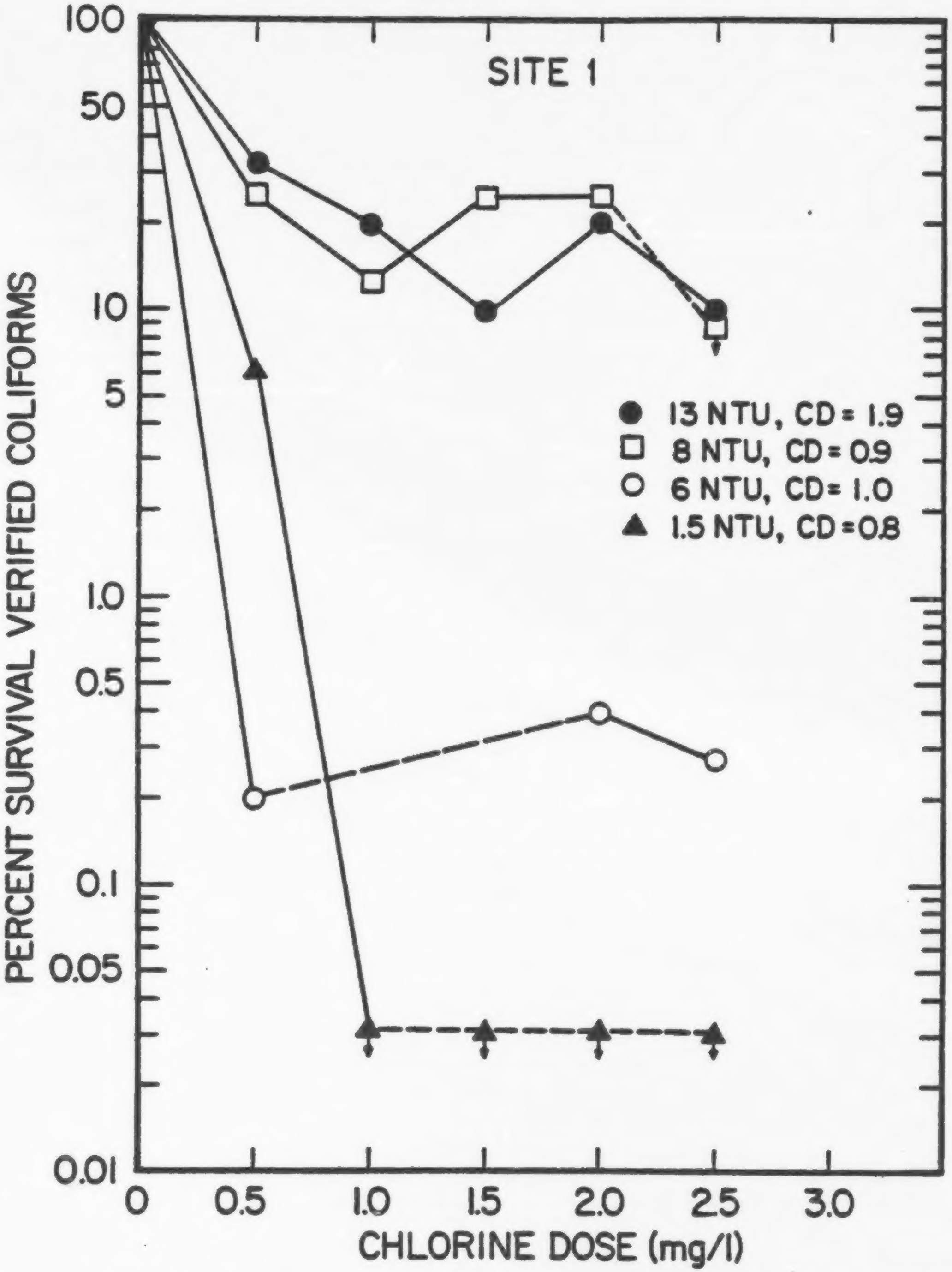

Fig. 16. Coliform persistence in turbid chlorinated water. Exposure to chlorine was for 1 hr. at 10°C. (Abbreviations: NTU, nephelometric turbidity units; CLDMD, chlorine demand) From: LeChevallier *et al*. (1981)

solved substances in the filtrate while the particles present exerted only 10 percent of the chlorine demand. In another recent study, Katz (unpublished data) determined the chlorine demand of 94 raw water samples collected in various geographical areas in the U.S. The distribution of chlorine demand in the filtrate and residue fractions of these samples is shown in Table 8.

Table 8. Distribution of Chlorine Demand in Raw Water Samples

		Chlorine Demand			
		Filtrate[a]		Residue	
Number of Samples	Turbidity Range (NTU)	mg/L (ave)	Percent of Total	mg/L (ave)	Percent of Total
10	0.05-1	0.53	99.1	0.005	0.9
30	1-5	1.41	96	0.062	4.
13	5-10	1.82	93	0.14	7
11	10-20	1.86	90	0.21	10
30	> 20	2.09	77	0.60	23

[a] Turbidity reduction by filtration through an 0.45 um membrane filters usually exceeded 85 percent

From: Katz (Unpublished data).

These data show that as raw water turbidity increases, chlorine demand also increases and that 90 percent or more of the demand is associated with the dissolved materials at turbidities of < 20 NTU. The results also indicate that as turbidity increases, the proportion of demand associated with the solids fraction increases, amounting to 23 percent of the demand in samples with turbidities greater than 20 NTU.

The results of these studies indicate that the solids present in raw waters contribute little to the disinfectant demand of the water. The results presented apply directly only to systems employing disinfection only for drinking water treatment. In systems employing complete treatment, turbidity present in the finished water may consist in part of those particles not removed by water treatment processes and in part of materials added during treatment e.g. alum floc. It is unlikely that such materials would contribute significantly to disinfectant demand especially because disinfectant residuals often are present throughout the course of treatment and in finished water during the detention period prior to entry into the distribution system. However, certain complex organic particles such as humic materials react with chlorine and other disinfectants very slowly over a period of 7 days or more (Katz, unpublished data; Stevens *et al.*, 1976) and, if present, could be expected to exert demand after entry into the distribution system. Also, it is possible that certain particles present in finished water could contribute indirectly to disinfectant depletion by serving as sites for concentration of nutrients and subsequent attachment and growth of microbial flora present in the distribution system. Byproducts of the microbial growth could create substantial disinfectant demand, thereby causing depletion of the residual disinfectant present.

TURBIDITY INTERFERENCE WITH INDICATOR DETECTION

Turbidity can have an important effect on the detection of coliforms in drinking water. For example, interference with the MF procedure can be caused by suspended material on the membrane surface during sample filtration. Gelatinous or hygroscopic materials such as alum flocs or algal cells can clog the membrane pores and make it difficult or impossible to filter the required 100 ml volume. This layer on the membrane also can cause confluent bacterial growth to develop during subsequent incubation. Geldreich *et al*. (1978) and Geldreich (1982) tested 613 water samples obtained from dead end mains in the Cincinnati water supply distribution system for coliforms and turbidity. More of the samples were positive for coliforms by the 5 tube MPN procedure than by the MF method. Of the 613 samples, 6 percent were positive by the MPN procedure and 0.8 percent were positive by the MF method. When the positive coliform samples were correlated with the sample turbidity measurements, it appeared that turbidity interference was a major factor of low coliform detection in the MF tests. No coliforms were found by either method when the samples contained less than 1 TU. In the 1-5 NTU range more coliforms were detected by both methods than in any other turbidity range tested.

LeChevallier *et al*. (1981) studied the effect of turbidity on chlorination efficiency and coliform persistence in drinking water. They recovered typical coliforms from apparently negative MF membrane filters and found that coliform masking increased as the turbidity of the chlorinated water increased. The magnitude of masking increased from < 1 coliform/100 mL in water samples of < 5 NTU to > 1 coliform/mL in water of > 5 NTU.

Seidler and Evans (1982) placed filter membranes that showed no typical coliform colonies or no visible bacterial colonies into tubes of lauryl tryptose broth and processed them in a manner similar to the standard MPN method. They found that, at a turbidity of 2 NTU or less, 5 of 36 samples were falsely negative. At 5 NTU, 15 of 36 were falsely negative and at turbidities in excess of 10 NTU, 80 percent apparently were falsely negative, indicating that excessive turbidity had interfered with the growth of coliforms. Herson and Victoreen (1980) reported that coliform inhibition is dependent on the ratio of coliform numbers to non-coliform numbers. More non-coliforms than coliforms increased the amount of inhibition of the coliforms. They also reported that coliform inhibition was not observed unless the non-coliform and coliform organisms were growing and increasing in number. They claimed that the inhibition of coliforms on membrane filters was not due to the turbidity *per se*. Rather, inhibition was probably caused by the numbers and growth of noncoliform bacteria.

Olson (1982) found that out of 448 bacterial isolates from a chlorinated surface water supply, 22.1 percent produced bacteriocin-like substances inhibitory to *Escherichia coli*, *Enterobacter aerogenes*, and *Klebsiella* sp. In an unchlorinated groundwater supply 7.9 percent of 696 isolates produced bacteriocin-like substances.

Another effect of turbidity on coliform detection can be the accumulation of particles in the distribution system, especially in slow flow sections and dead ends. The particles may form a sediment and become hardened by carbonate deposits. With a depletion of chlorine residual, bacterial regrowth could occur and these microorganisms would then interfere with coliform detection (Geldreich et al., 1978; LeChevallier et al., 1980; Reitler and Seligmann, 1957; Hutchinson et al., 1943).

These results suggest that the most probable number (MPN) method for total coliforms may be the method of choice with water samples containing turbidity that interferes with the membrane filter (MF) procedure. However, the current MPN method limits the routine sample size to 50 ml compared to 100 mL for the MF procedure. Adsorption of coliforms to the turbidity particles, nonuniform distribution of coliforms and settling out of heavier particles are all factors that can affect the MPN results. The data of Seidler and Evans (1982) indicate that turbidity increases in the range of 2 to 5 NTU can cause decreased recovery of coliforms by the MF method. The available data do not show whether or not turbidity levels in the range of 1 to 5 NTU cause more interference with coliform detection than turbidity levels of < 1 NTU. Clark (1968) developed a presence-absence (P-A) test for coliform detection that also uses 100 mL of sample. This procedure is listed as a Tentative Method in the 16th edition of Standard Methods for the Examination of Water and Wastewater. Turbidity interference with this test has not been determined, but probably would be similar to that of the MPN test.

SUMMARY

The available evidence suggests that, of the wide variety of inanimate particles present in water, only pathogenic microorganisms and perhaps asbestos fibers have direct human health effects. These two groups constitute only a very small portion of the particulate matter normally found in water. In contrast, many types of particles may be indirectly important in serving as sites for sorption and concentration of toxic contaminants or by protecting pathogenic microorganisms from inactivation by disinfectants. While the potential for human health effects due to sorbed toxicants is recognized, little research has been conducted in this area. In contrast, a growing body of evidence suggests that protection of pathogenic microorganisms by association with particulate matter can be an important factor in their survival of water treatment processes, particularly disinfection. While adsorption of microorganisms onto surfaces offers little protection, more intimate association with particulate matter in materials such as alum flocs, feces or wastewater effluent solids appears to offer varying degrees of protection from disinfectant action to a portion of the microbial population present.

The results of several studies indicate that particulate matter in water causes only a minor part (< 10 percent) of the disinfectant demand in raw waters. There is evidence that certain types of turbidity can interfere with detection of coliforms at turbidity levels of 2 to 5 NTU. Such effects are especially evident when the membrane filter method is used.

IV TURBIDITY AS AN INDICATOR OF TREATMENT EFFICIENCY

The turbidity of raw surface waters alone cannot be used to predict the presence or absence of particles of health significance, but turbidity of treated waters sometimes can be used to estimate water quality. For instance, a mountain stream water source which meets the 1 NTU MCL could contain enough *G. lamblia* cysts to cause disease, based on the infective dose estimates (< 10 cysts) given by Rendtorff (1979). Similarly, the number of asbestos fibers could range as high as 1×10^9 to 1×10^{10} particles/L and the water would still be well within the 1 NTU MCL. On the other hand, another mountain stream water source could be very turbid during heavy runoff periods but the particles constituting the turbidity might consist primarily of materials having no health significance.

When waters have been treated by processes designed to remove particles, under certain circumstances relationships have been found to exist between the turbidity of the filtered water and the numbers of health significant particles in the water. These relationships are dependent upon the filtration process used. The processes usually used to clarify drinking water, rapid granular media filtration, slow sand filtration, and diatomaceous earth (DE) filtration, will be discussed individually below.

RAPID FILTRATION

Rapid granular media (sand, dual media, or mixed media) filtration generally includes coagulation, flocculation, sedimentation, and filtration. If raw water quality is very good, sedimentation and perhaps flocculation can be omitted from the treatment train. Granular media filtration for many years involved use of a single medium (sand). In the 1960's dual media and mixed media were studied and adopted. Recently, deeper (several feet) beds of single filter media have been designed for some filtration plants.

The key to effective filtration by this process, and thus to effective removal of turbidity-causing particles, is proper coagulation prior to filtration. Relationships between filtered water turbidity and the concentration of specific types of particles such as asbestos or *Giardia* cysts in filter effluent are valid only for waters that have been *properly* coagulated. Factors involved in coagulating water in a way that yields the desired quality of filtered water are numerous, and can include mixing time, mixing intensity, pH, type of coagulant (alum, iron salts, polymer, etc.), coagulation chemical doses, order of chemical addition, water temperature, and constituents of the raw water. Some of these factors are beyond the control of plant operators. Those most easily varied by the operator are pH and chemical dose.

When chemical doses are too high or too low, or when no coagulating chemicals are used, serious problems can result. An incorrect chemical dose, either too little or too much (especially when polymers are used), can cause incomplete particle destabilization and result in passage of large numbers of particles through the filter. Trussell *et al.* (1980) showed the importance of adequate coagulation in a direct filtration pilot plant study. Filtration with no coagulation removed about 90 percent of the particles larger than 2.5 um, whereas coagulation and filtration removed in excess of 99 percent. Filtration without coagulation reduced turbidity from 0.55 to 0.24 NTU. Chemical addition and filtration reduced turbidity from 0.57 NTU to 0.11 NTU. The relationship between granular media filter effluent turbidity and water quality has been considered for a variety of particles, including viruses, bacteria, *Giardia* cysts, and asbestos fibers. The findings indicate that filtered water *turbidity* and the extent of turbidity removal in the treatment process do influence microbial water quality.

Microorganism Removal

Virus removal by granular media filtration was studied by the U.S. P.H.S. (Robeck *et al*. 1962). Pilot plant filtration experiments at flow rates of 5 to 15 meters/hr 1 gpm/ft^2 = 2.44 m/hr showed that when uncoagulated water was filtered at these rates, only 1 to 50 percent of the influent virus dose could be removed. Properly coagulated water, filtered without sedimentation, resulted in removals in the 90 to 99 percent range, generally exceeding 98 percent. When water was coagulated, flocculated, settled and filtered, virus removals consistently exceeded 99 percent.

An American Society of Civil Engineers Committee (Committee on Public Health Activities, 1961) concluded from a review of the literature that removal of viruses, coliforms, total bacteria and turbidity by water treatment processes could be considered to be roughly parallel. Clarke *et al*. (1964) reported that chemical flocculation, properly applied, is highly *effective* in removing viruses and bacteria from water and that the removal of the microorganisms paralleled the removal of turbidity. Sproul (1980) reviewed literature on virus removal by water and wastewater coagulation processes and lime treatment and concluded that turbidity removal can be used as a process control for virus removal by these processes. Hoff and Akin (1983) in a recent review of virus removal by drinking water treatment processes, including sedimentation and filtration processes, also indicated that turbidity removal by these processes is indicative of virus removal efficiency.

The work of Robeck *et al*. (1962) indicated that careful control of filtered water turbidity was *necessary* for effective virus removal by filtration. When filters were producing water well below 1.0 NTU and virus passage was quite low, an increase in turbidity could signal a large increase of virus passage even when the higher turbidity of the filtered water did not exceed 1.0 NTU.

Treatment of water by direct filtration was studied by McCormick and King (1982). Average raw water turbidity in their studies ranged from 2 to 24 NTU, but was 10 NTU or lower for a majority of the tests. The treatment process included coagulation, flocculation and filtration. Total coliform counts in the raw water ranged from < 1 to 2300 cells/100 mL. They reported, "When turbidities in the filtered water were reduced to 0.1 NTU or less, coliform bacteria removal was practically 100 percent." The reduction in turbidity under those conditions was substantial, from 95 percent to 99 percent or greater.

Recent rapid rate filtration research (Hendricks, 1981, 1982, 1983) has produced similar results. Removal of *Giardia* cysts, cyst-sized particles, standard plate count organisms, and total *coliform* bacteria was investigated using a pilot plant employing coagulation, flocculation, sedimentation, and filtration using sand and dual media. At times some pretreatment processes were omitted before filtration. The raw water source was Horsetooth Reservoir. This water contains very fine (less than 1 um) turbidity-causing particles. Work by Lange et al. (1984) showed that two third of the turbidity in Horsetooth Reservoir water remained after filtration through a 1.2 um pore size membrane filter (Fig. 17). One fourth of the turbidity remained after filtration through a 0.45 um pore size membrane.

Results are given in Table 9. The trends observed in this work are similar to the results of McCormick and King (1982) who found coliform removal of 99.0 percent or higher in 37 data sets, of which 31 sets (84 percent) had turbidities of 0.10 NTU or lower. The Colorado State University results by Hendricks showed that 69 percent of the filtered water samples having turbidities of 0.10 NTU or lower had < 1 coliform/100 mL, and in 71 percent of these samples, coliform removal by coagulation and filtration met or exceeded 99.0 percent. These levels of treatment were attained less frequently when filtered water turbidity exceeded 0.10 NTU. Results of Hendricks, (1981, 1982, 1983) suggest that to attain 99 percent removal of coliforms or low coliform counts in filtered water before disinfection is practiced, filtered water turbidity should be 0.10 NTU or lower.

TABLE 9. Influence of Filtered Water Turbidity on Coliform Removal by Coagulation and Filtration, CSU

Filtered Water Turbidity Range NTU	Number of Samples	Percent of Samples with Coliform ≤ 1/100 mL	Percent of Samples with Coliform Removal ≥ 99.0%
≤ 0.10	42	69%	71%
0.11 to 1.4	46	37	50
> 1.4	19	47	42

From: Hendricks, (1981, 1982, 1983) and Bellamy et al. (1983)

The influence of turbidity on the removal of *Giardia* cysts has been studied in a number of research projects. Cysts for the research have been obtained from mice (*G. muris*), diseased humans (*G. lamblia*), and dogs. Logsdon et al. (1981a), showed that *G. muris* cysts could pass through granular media filters, even though the filtered water turbidity did not exceed the 1 NTU MCL. This occurred when coagulant doses were inadequate or interrupted or when raw water was not coagulated. Cysts also broke through during a filter run when coagulant feed was interrupted, the rate of filtration was

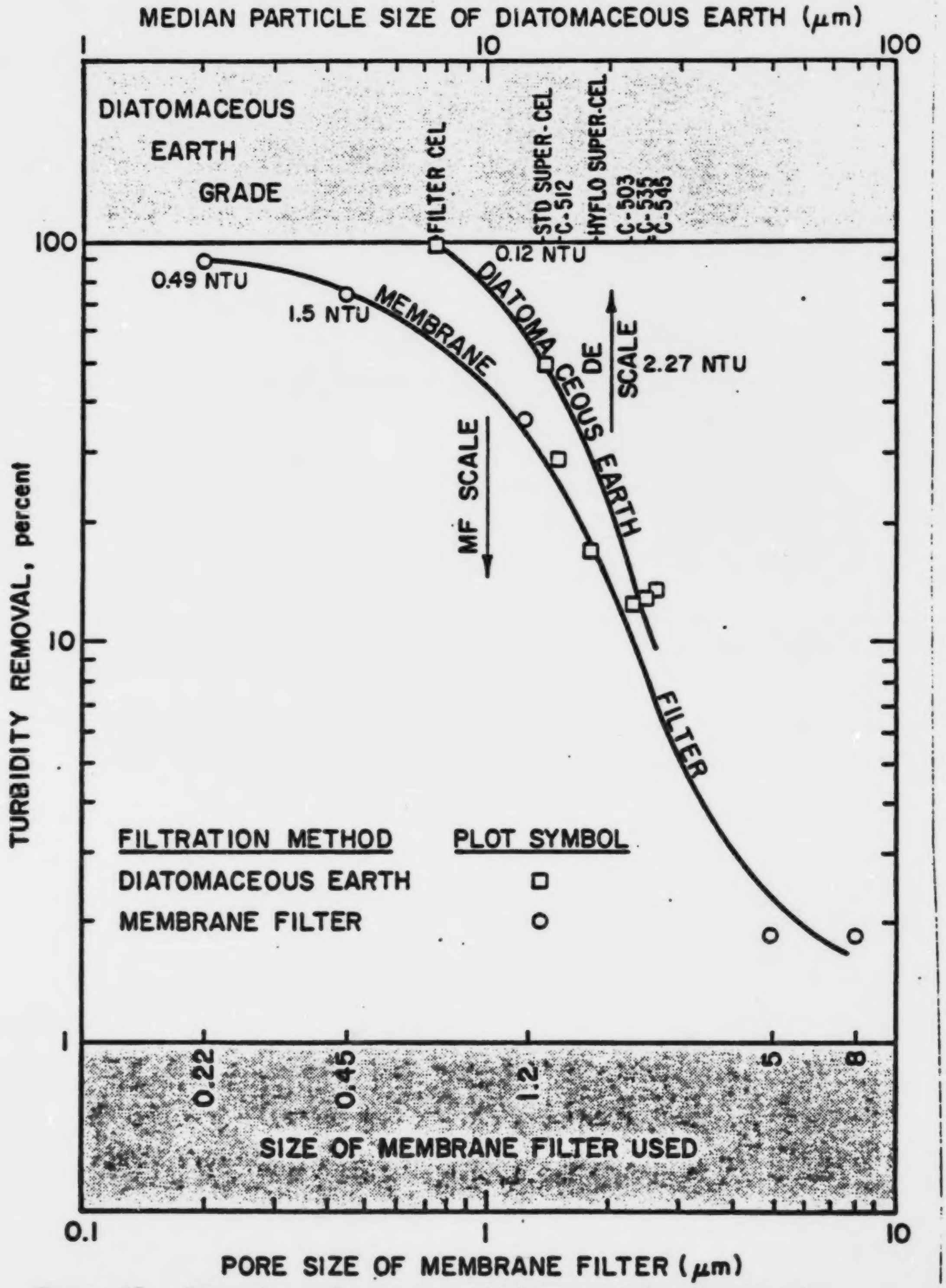

Figure 17. **Comparison of percent turbidity removals, Horsetooth Reservoir water, by membrane filters of different sizes and diatomaceous earth of different grades.**
(From Lange et al. 1984)

abruptly increased, or a turbidity breakthrough occurred at the end of a filter run. However, when the dual media filter was operated at 10 meters/hr (4 gpm/ft^2) and the raw water was properly coagulated, *G. muris* cyst reductions generally were 99 percent or higher. This work indicated that when filtered water turbidity was well below 1.0 NTU, cyst removal was effective, but data were insufficient to define the level of turbidity that would be a reliable indicator of successful filtration.

Pilot plant investigations by DeWalle *et al*. (1983) have contributed to understanding the relationship between filtered water turbidity and the concentration of *Giardia* cysts in drinking water. The pilot plant used for this study had rapid mixing, flocculation, sedimentation, and filtration. Unfiltered Seattle tap water from the Tolt Reservoir was used as a raw water source. The first seven filter runs for *Giardia* cyst removal were made using the coagulation/sedimentation unit followed by filtration. Runs made thereafter were direct filtration runs, bypassing the sedimentation unit. The results of cyst spiking in the first seven runs generally showed high (96 to 99.9 percent) cyst removals at cyst levels of 23 to 1100 cysts/L. The removal efficiency seemed to decrease at low spiking levels. Removal was only 30 percent at a cyst concentration of 2.3 cysts/L in raw water. These results are shown in Table 10.

TABLE 10. Performance of Each Filter Run with Cysts Added Directly to Rapid Filter

Run No.	Filtration Rate m/hr	pH	Dosage Cysts/L	Cyst Removal
3	5	6.7	984 Filter B	99.96%
4	6.3	6.3	1093 Filter C	99.95
5	5.9	7.2	23 Filter C	97
6	5.9	6.4	30 Filter C	97
7	5.6	7.2	2.3 Filter C	30

From: DeWalle *et al*. (1983)

After a series of direct filtration runs had established operating conditions for effective removal of cyst-sized particles, additional runs were made with *G. lamblia* cysts. During most of these filter runs, about 20 million cysts per run were added to the raw water. These tests established the importance of good coagulation practice. Results are shown in Table 10. At optimum conditions cyst removal was consistently high. An alum dosage of 12 mg/L, pH 6.2, and a filter loading rate of 6.1 m/hr (2.5 gpm/ft^2), gave a 99.7 percent removal of cysts following the 1.25 hour filter ripening period. Later in the run, cyst reduction was 99.94 percent and the effluent turbidity was constant at 0.02 NTU when influent turbidity was 1.2 NTU.

Table 11 also shows that filtered water turbidity could be used as a guide to cyst removal efficiency. Cyst removal exceeded 99.0 percent ten times. In 7 of the 10 instances, the filtered water turbidity was less than 0.10 NTU. Cyst removal was less than 99 percent on five occasions, and each time the filtered water turbidity exceeded 0.10 NTU (actual range was 0.19 to 0.52 NTU).

In the Colorado State University investigation of Giardia cyst removal by granular media filtration, cysts from infected dogs were used. Results of pilot plant filter runs are presented in Table 12. The results show that the percentage of effluent samples containing 5 or fewer cysts/L declined as the filtered water turbidity increased. The same trend was not seen for samples showing cyst removals of 99 percent or greater.

The common factor among the findings of the three Giardia research projects cited above is the need to attain low filtered water turbidity in order to attain effective cyst removal. Granular media filters do not operate in a dependable manner unless the raw water is properly pretreated. Adequate coagulation is the minimum treatment needed, when direct filtration is used. When clear waters (about 10 NTU or lower) are filtered, barely meeting the 1 NTU MCL will not assure that granular media filtration will effectively remove the cysts. Research results indicate that the likelihood of producing water that has the lowest practical concentration of cysts is much greater when filtered water turbidity is 0.10 NTU or lower.

Asbestos Fiber Removal

Removal of asbestos fibers by granular media filtration has been studied extensively on Lake Superior and in the Pacific Northwest. Extensive pilot plant studies were carried out using Seattle's Tolt Reservoir supply, and recently the City of Everett started operation of a 50 MGD direct filtration plant. The design of this plant was based upon a pilot plant study conducted at Lake Chaplain, Everett's water source.

The results of the above studies and others were reviewed (Logsdon et al. 1981), and a filtered water turbidity of 0.10 NTU was recommended for removal of asbestos fibers at granular media filtration plants. The 0.10 NTU value is based mainly upon analysis of data from the Duluth (Logsdon, 1979) and Seattle (Kirmeyer, 1979) pilot plant research projects and the results obtained since 1977 at Duluth's filtration plant. These results show that fiber counts tend to be higher when filtered water turbidity exceeds 0.10 NTU and lower when turbidity is 0.10 NTU or below.

TABLE 11. Cyst Removal During Direct Filtration at UW Pilot Plant

Run No.	Alum Coagul. and Dosage mg/L	pH	Filter Loading Rate m/hr	Cyst Addition							
				Total Dosage	Filt. Infl. Dosage	Cyst Removal %	Elapsed Time Hrs:Min	Infl. Turbidity NTU	Effl. Turbidity NTU	Turbidity Removal %	Headloss cm
72	None	6.5	6.1	$2.0 \cdot 10^6$	$6.6 \cdot 10^5$	48	4:30	0.73	0.39	47	31.5
73	12.0	6.2	6.1 4.3	$12.7 \cdot 10^6$ $20.0 \cdot 10^6$	$3.8 \cdot 10^6$ $4.2 \cdot 10^6$	99.7 99.94	1:15 26:00	1.24 1.19	0.03 0.19	98 84	34.5 143.5
74	12.0	6.2	9.7	$15.5 \cdot 10^6$	$7.3 \cdot 10^6$	99.93	1:00	1:37	0.04	97	57.2
76	12.0	6.2	9.4	$19.0 \cdot 10^6$	$8.7 \cdot 10^6$	99.98	7:00	1.14	0.02	98	104.6
77	7.0	6.2	9.7 8.6	$19.2 \cdot 10^6$ $20.4 \cdot 10^6$	$9.8 \cdot 10^6$ $9.4 \cdot 10^6$	99.7 99.87	1:00 16:00	1.94 0.81	0.24 0.03	88 96	60.7 155.4
78	4.0	6.2	10.1 8.6	$21.4 \cdot 10^6$ $20.2 \cdot 10^6$	$10.7 \cdot 10^6$ $8.8 \cdot 10^6$	64 91.8	2:30 72:30	1.31 1.35	0.52 0.37	60 73	61.2 183.9
79	12.0	6.8	9.7 8.3	$21.5 \cdot 10^6$ $21.5 \cdot 10^6$	$10.3 \cdot 10^6$ $8.4 \cdot 10^6$	95.4 99.4	1:00 10:00	0.95 1.02	0.28 0.04	71 96	73.4 209.0
80	12.0	5.6	9.7	$20.4 \cdot 10^6$	$10.0 \cdot 10^6$	99.8	1:00	1.73	0.03	98	64.0
81	12.0	5.6	9.7	$20.4 \cdot 10^6$	$9.8 \cdot 10^6$	99.8	7:00	1.78	0.02	99	104.4
82	Cat. Floc T1 5.0	6.4	9.7 9.7	$20.1 \cdot 10^6$ $20.1 \cdot 10^6$	$9.8 \cdot 10^6$ $9.8 \cdot 10^6$	95.9 99.9	1:00 21:00	0.92 0.80	0.23 0.27	75 66	58.2 68.3

From: DeWalle *et al.* (1983)

TABLE 12. Influence of Filtered Water Turbidity on *Giardia* Cyst Removal by Coagulation and Filtration, CSU

Filtered Water Turbidity Range NTU	Number of Samples	Percent of Samples with	
			Cyst Removal
		≤ 5 cysts/L	≥ 99.0%
< 0.10	23	78%	83%
0.11 to 1.4	28	36%	43%
1.4	3	33%	33%

From: Logsdon (1983a)

Problems with and limitations of the use of a turbidity value as a guide to operating filters for asbestos fiber removal should be set forth clearly. The data on which the 0.10 NTU value is based were obtained at filtration plants treating water having low turbidity - generally 1 NTU and nearly always less than 5 NTU. Also, treatment involving coagulation must be done in a way that completely destabilizes the particles in the water. The use of inadequate coagulation chemicals can result in less than complete particle destabilization and may lower fiber removal efficiency.

The relationship between filtered water turbidity and fiber count may be different in waters that are more turbid than Lake Superior and the Tolt Reservoir. For example, in Contra Costa County, California, monitoring data from the Antioch and Pittsburg plants showed effluent turbidities between 0.1 and 0.4 NTU (Logsdon, 1979) while effluent turbidity at the Bollman Plant was 0.06 NTU or lower. Nevertheless fiber counts in filtered water were similar for all three plants, below 0.3 x 10^6 f/L in 12 of 14 instances. Two of these filtered water samples were in the 0.7 - 0.8 x 10^6 f/L range, and six samples had below detectable limits (BDL) or not statistically significant (NSS) values. Raw water turbidities generally were between 20 and 40 NTU.

At the San Geronomo plant in Marin County, California, two of six filtered water samples had counts above 1 x 10^6 f/L (2 x 10^6 and 12 x 10^6). These samples had turbidities of 1.0 to 0.6 NTU and 0.6 to 0.3 NTU respectively. Raw water turbidity at the San Geronomo plant was 5 NTU for one of the above samples and 46 NTU for the other.

The results from Contra Costa County and Marin County suggest that attaining a filtered water turbidity of 0.10 NTU or less is not as important when the raw water is not exceptionally clear, i.e. somewhat above 1 NTU, before filtration. Perhaps when raw water contains enough clays, algae, bacteria and other particles to raise the turbidity significantly above 1 NTU, the asbestos fibers become associated with the other particles and are removed along with them.

Data suggest that asbestos fiber removal can be accomplished when filtered turbidity exceeds 0.10 NTU when the raw water is turbid. Sufficient data to define "turbid" waters for which this is true have not been obtained, however, nor is the upper limit for filtered water turbidity that is associated with good fiber removal apparent. Limited data suggest that 0.4 NTU might be adequate, but 0.6 NTU might not.

A more recent report (McGuire et al. 1983) questioned the adequacy of using 0.10 NTU as a surrogate level for asbestos fibers. They reported that filtered water chrysotile concentrations were frequently in the range of 1×10^6 f/liter (f/L) to 50×10^6 f/L at three treatment plants of the Metropolitan Water District of Southern California (MWDSC) where raw water fiber counts generally ranged from 200×10^6 f/L to 2000×10^6 f/L. This was observed even when filtered water turbidity in the plant effluent was near or below 0.10 NTU. They stated, "Achieving the 0.10 NTU goal does not guarantee low asbestos levels but can help reduce the levels when influent concentrations are as high as those recorded in this study. More research is needed to identify the mechanism by which asbestos fibers break through filters when the influent asbestos concentrations are 500-1000 MFL. It appears from these data that there is little hope in using 0.10 NTU as a surrogate regulatory level for asbestos fibers in treated drinking water." They concluded that attaining a turbidity level of 0.10 NTU did not guarantee a low asbestos concentration ($< 1 \times 10^6$ f/L).

This observation does not contradict the Logsdon et al. (1981) observation. Attaining 0.10 NTU enhances the likelihood of producing water with low fiber counts, but it does not guarantee it.

When the available data are considered, it can be concluded that too little data and too much uncertainty exist now to suggest an operating goal other than 0.10 NTU. Treating to attain 0.10 NTU would require careful operation and excellent equipment performance at plants treating turbid water. A distinct advantage of such an exacting quality goal is that to achieve it, fluctuations in filtered water quality would not be permitted. A rise in turbidity, caused by run-terminating breakthrough or by a coagulant feed malfunction, could be a signal for immediate corrective action by the plant operator. Preventing the production of higher turbidity water would prevent the sloughing of asbestos fibers from filters and thus would improve filtered water quality.

SUMMARY

Properly designed and operated granular media filtration plants have the capability of removing a variety of particulate contaminants, ranging in size from asbestos fibers and viruses to bacteria to cysts. Removal of particles is most effective when turbidity of the filtered water is low, well below 1 NTU. Turbidity breakthrough has been observed to indicate increases in the concentration of asbestos fibers, viruses, and cysts in filtered water.

SLOW SAND FILTRATION

Slow sand filtration originated in England in the early to middle 1800's. The first slow sand filters in the United States were built in the late 1800's and the process is still being used in some areas. Labor needed for cleaning, land requirements, and the unsuitability of the process for treating high turbidity surface water led to the decline in the use of slow sand filtration.

The mechanisms of slow sand filtration are to some extent similar to those of rapid filtration, but important differences exist. The most important difference is the role of living organisms in the filtration process. Slow sand filtration, according to Huisman and Wood (1974), can be thought of as biological filtration. They state, "Biological (or slow sand) filtration is accomplished by passing raw water through a bed of sand. During its passage the particulate impurities are brought into contact with the surface of sand grains and held in position there. Those that consist of inert material are retained until eventually removed during the cleaning process, while those capable of chemical or biological degradation are converted into simpler forms that are either carried away in solution or remain, with the inert material, for subsequent removal." This discussion of slow sand filtration mechanisms is based upon Huisman and Wood's Chapter 3, Theory of Biological Filtration.

One shortcoming of much of the literature on slow sand filter performance is the lack of accompanying turbidity data. Because of the nature of slow sand filtration, however, this may not be a serious problem. Slow sand filtration is primarily a biological process, and as such it can accomplish excellent removals of biological particulate contaminants. The process is effective because an ecosystem is established within the filter.

The ability of slow sand filters to remove bacteria from drinking water was shown by the decline in disease and death rates for waterborne diseases such as cholera and typhoid fever. In the early years of slow sand filtration and microbiology, some experimental data also were obtained, and the results generally showed that removal of bacteria could exceed 99 percent, but declines in removal occurred during winter when water temperatures were lowest. Modern turbidimeters were not available during the late 1800's and early 1900's, so even though the bacterial removal capabilities of slow sand filters were proven, useful data on turbidity of the filtered water were not obtained.

The EPA Drinking Water Research Division (DWRD) has conducted research and funded studies on slow sand filtration. In this research, clear (about 1 NTU) water from a gravel pit spiked with residential sewage was filtered. Water samples were collected and analyzed for turbidity, particle count, standard plate count, and coliforms. Results of this research are summarized in Table 13. Coliform counts generally were reduced by 99 percent or more. Coliforms were not detected in most filtered water samples even when raw water coliform counts ranged between 1,000 and 10,000 per 100 mL. After a problem of growth of standard plate count organisms on soft plastic discharge tubing was solved by changing to stainless steel discharge tubing, a two log reduction (about 99 percent) of standard plate count organisms typically was observed. Examination of coliform counts and filtered water turbidity data shows almost no relationship between the two, except for the start-up period when new, clean sand had been installed and the ecosystem was becoming established in the filter. During this extended ripening period, coliform counts and turbidity became progressively better.

TABLE 13. Turbidity and Coliform Counts from EPA Pilot Slow Sand Filter

Run Number	Turbidity when Coliform Counts $\leq$ 1/100 mL		Turbidity when Coliform Counts $\geq$ 1/100 mL	
	Average	Range	Average	Range
1 - Ripening Only	-	-	0.32	0.22-0.58
1	0.20	0.16-0.26	-	-
2	0.24	0.18-0.38	0.26	0.18-0.36
3	0.39	0.20-0.60	-	-
4	0.24	0.21-0.30	-	-
5	0.24	0.20-0.30	-	-
6	0.20	0.16-0.23	0.24	one sample

From: Fox _et_ _al_. (1983)

Cleasby (1983) using a surface water source studied turbidity and microorganism removal by slow sand filtration. The maximum terminal head loss available was 135 cm. The length of the filter runs varied seasonally. The best raw water occurred during the winter under ice cover, when the longest run was 123 days. The shortest runs (9 days) occurred in the summer during periods of severe algal blooms.

The results of these studies are shown in Table 14. Although run length and raw water quality varied, filtered water quality consistently was good. The filtered water turbidity for the first two runs (A & B) was higher than for the remaining runs. A comparison of filtered water turbidities and coliform removals in Table 14 shows that generally when turbidity declined during the run, the removal of coliforms improved. This occurred throughout run B, as well as after the initial improvement periods of runs D, E, F, G, I, and J. These results suggest that changes in effluent turbidity from an operating slow sand filter might indicate changes in bacteriological quality, and that lower turbidity is more desirable than higher turbidity. Note that the ranges of filtered water turbidity were all lower than the 1 NTU MCL.

TABLE 14. Comparison of Total Coliform and Turbidity Data for Initial Days and Remainder of Slow Sand Filter Runs

	Influent	Effluent					
		First 2 days			Remaining Days		
Run Number	Mean Coliform per 100 mL	Mean Coliform per 100 mL	% Red.	Mean Turbidity NTU	Mean Coliform per 100 mL	% Red.	Mean Turbidity NTU
A	2384	No data		0.42	159	93.3	0.39
B	0	2		0.28			
B (12/3-16/81)	9716				455	95.3	0.26
B (12/16-2/17/82)	2119				15	99.3	0.20
B (2/17-4/3)	500				1.6	99.7	0.19
C	737	1.7	99.8	0.24	1.0	99.9	0.24
D	47	8	83.0	0.53	1.5	96.8	0.23
E	112	12	89.3	0.32	3.7	96.7	0.13
F	191	18	90.6	0.14	0.5	99.7	0.10
G	74	1.4	98.1	0.10	0.4	99.5	0.05
H	42	2	95.2	0.14	Bad data		0.14
I	121	10	91.7	0.46	0.5	99.6	0.10
J	215	18	91.6	0.13	0	100.0	0.07
K	1100	6	99.5	0.10	0.7 0.7	99.9	0.07

From: Cleasby (1983)

In another investigation of slow sand filtration, Hendricks, (1981, 1982, 1983) noted the lack of a relationship between removal of biological particles (total coliform, standard plate count, and fecal coliform) and removal of turbidity when Horsetooth Reservoir water was the raw water source. Average filtered water turbidity from all filters exceeded 1 NTU, ranging from 3.5 to 4.1 NTU.

The failure of the slow sand filters to produce filtered water meeting the 1 NTU MCL was noted (Hendricks 1981). When the filtered water turbidity exceeded expected values, samples of raw water were subjected to additional testing to determine the characteristics of the particles. The results are shown in Table 15. Because only about half of the turbidity could be removed by filtration through a 0.45 um membrane filter, the researchers concluded that the remaining turbidity-causing particles were very fine. Later some of the fine particles passing through the slow sand filter were reported to be kaolinite and montmorillonite clay particles, based upon X-ray analysis and scanning electron microscope testing of residue on 0.2 um membrane filters.

TABLE 15. Filtration Data--Horsetooth Water

Date	Unfiltered NTU	Filtered 1 um Cartridge NTU	Filtered[1/] 0.45 um Membrane NTU
9/29	7.0	5.7	
10/2	6.5	5.0	
10/3	7.5	5.9	
10/9	6.3	4.9	
10/12	6.9	5.5	3.8
10/18	6.8	5.3	3.9
12/23	9.5	7.6[2/]	4.5[3/]

[1/] Filtered under gravity head only

[2/] Average removal--21 percent

[3/] Average removal overall--47 percent, and from 1 um to 0.45 um--33 percent

From: Hendricks (1981, 1982, 1983)

The results for bacterial removal by slow sand filtration have shown that whereas this process is effective for coliform removal when filters are designed and operated within usual limits of sand size and depth and filtration rate, some waters do contain particulate matter that is not readily removed and that does scatter light, indicating turbidity when tested in a nephelometer. Turbidity removal cannot be used always as an indicator of bacteria removal by slow sand filters.

Slow sand filtration for *Giardia* cyst removal has been studied extensively (Bellamy *et al.* 1983) using a slow sand filter having a sand bed with a well developed biological population (minimum sand bed exposure was 29 weeks). *Giardia* cyst removals were excellent, even though in some cases the filter had been scraped and the age of the schmutzdecke was as low as three weeks. The lowest percentage of cyst removal attained with the developed sand bed was 99.77 percent, and cyst removal was 99.90 percent or greater in 22 of 24 observations. In 12 of 24 observations, no cysts were found when filtered water volumes ranging from 81 L to 1,440 L were passed through 5 um pore diameter membrane filters to test for presence of *Giardia* cysts. These results were obtained even though the filtered water did not meet the 1 NTU MCL.

Horsetooth Reservoir was the raw water source for tests for *Giardia* removal as well as for tests for coliform removal. In fact, in numerous test runs, behavior of both kinds of organisms was studied. Slow sand filtration was very effective for removing coliform bacteria and *Giardia* cysts, but the process was not effective for turbidity removal with the raw water used in this work. Because of the low standard plate counts (Elmund, unpublished data) in raw, unspiked, Horsetooth Reservoir water (on the order of 25 to 600 per 100 mL) the turbidity in both the raw water and the slow sand filter effluent is thought to have been caused by the fine clays present in this water. Based on the results described above, it would appear that turbidity removal by slow sand filtration cannot always be related to microorganism removal.

Removal of asbestos fibers by slow sand filtration appears not to have been studied. On the basis of the poor removal of small (< 0.47 um) clay particles in Horsetooth Reservoir waters, slow sand filters would not be expected to remove asbestos fibers efficiently.

DIATOMACEOUS EARTH FILTRATION

Diatomaceous earth (also referred to as DE or diatomite) filter operation consists of three steps: precoating, filtration, and filter cleaning. Precoating is accomplished by adding a measured amount of diatomite to filtered water and recirculating the slurry through the filter. During the filter runs, body feed diatomite is added to the raw water to maintain the porosity of the filter cake. This causes the thickness of the filter cake to increase during the run. Filter runs are terminated when head loss exceeds a predetermined value. The filter cake is removed from the septum and the spent diatomite discharged to waste. Filter leaves (septa) and filtration chamber are carefully cleaned to make the filter ready for a new precoating.

Research by Lange *et al.* (1984) recently has confirmed the earlier observation of Hunter *et al.* (1966) showing that fewer total coliforms passed through the DE filter as finer grades of diatomite were used. These results (Table 16)

TABLE 16. Five Hour Test Runs. Diatomaceous Earth Filter Removals of Turbidity, Total Coliform Bacteria and Standard Plate Count Bacteria

Grade of Diatomaceous Earth	Celite 545®	Celite 503®	Hyflo Super-Cel®	Celite 512®	Standard Super-Cel®	Filter Cel®
Median Particle Size of D.E. (um)	26	23	18	15	14	7.5
D.E. Particle Size 10% Finer than D_{10} (um)	12.8	10.4	5.2	4.3	3.1	1.5
Median Pore Size (um)	17.0	10.0	7.0	5.0	3.5	1.5
Turbidity Removal (%)	17	11	18	28	50	98
Influent NTU	4.6	4.6	4.6	4.6	4.5	5.4
Effluent NTU	3.8	4.1	3.7	3.3	2.3	0.12
Total Coliform Bacteria Removal (%)	28	68	82.9	97.0	>99.97	>99.84
Influent Conc. #/100 mL	34,000	4,450	4,000	2,380	6,100	640
Effluent Conc. #/100 mL	24,600	1,418	685	71	<1.7	<1
Standard Plant Count Bacteria Removal (%)	38	56	65	80	96.4	99.75
Influent Conc. #/mL	79,000	6,600	9,050	3,600	9,250	990
Effluent Conc. #/mL	48,800	2,936	3,126	737	737	2.5

Values are averages of six effluent samples and two influent samples which were taken during six test runs each lasting five hours.

From: Lange _et_ _al_. (1984)

show that removals of standard plate count organisms, total coliforms, and turbidity all improve as finer grades of DE were used. Because of the size differences between bacteria and the fine clay particles in Horsetooth Reservoir water, removal of turbidity-causing particles was less than the removal of microorganisms for most grades of DE (Table 17). The finest grade tested, Filter Cel®, was very effective for turbidity removal. This grade generally is not used in potable water treatment because of the high head loss caused by its small particle size.

Comparisons of turbidity removal by diatomaceous earth filtration and membrane filtration were again made, and membrane filtration results showed that nearly all of the turbidity-causing particulates passed a 5 um filter. A 1.2 um filter removed only about 36 percent of the turbidity. Similar results were obtained with Celite 512®. These results indicate that the turbidity-causing particles in Horsetooth Reservoir water are very small.

Research with alum-coated DE showed that diatomite onto which aluminum hydroxide had been precipitated was more effective than uncoated diatomite for removal of standard plate count organisms, total coliforms, and turbidity. With Celite 545® turbidity removal improved from 13 percent to 98 percent and total coliform removal increased from 49 percent to 99.86 percent. Results in Table 18 show that the alum coated diatomite removed smaller particles than uncoated DE and suggest that filtered water turbidity could be more closely related to the microbiological quality of DE filter effluent when the alum coating process was used.

Field tests of DE filtration were conducted using two mountain stream sources. Comparative bacterial and turbidity removal data are shown in Table 19 (Lange et al. 1984). Raw water turbidities varied from 0.55 NTU to 32 NTU. In these field tests the coarsest grade of diatomite, Celite 545®, was used. Coliform and standard plate count removals were less effective at the 4.9 and 9.8 m/hr filtration rates than at the commonly used rate of 2.4 m/hr. Turbidity removal was much better on these waters than on Horsetooth Reservoir water. The highest turbidity removal with the Horsetooth water was 24 percent when Celite 545® was used, and the average removal for all Celite 545® runs was 13 percent. In contrast, with Poudre and Dillon raw waters, turbidity removal ranged from 21 to 77 percent. Turbidity removal by diatomaceous earth filtration is in part a function of the nature of the water being treated. Thus, use of filtered water turbidity as a surrogate measure for bacterial passage through a DE filter is difficult at best, because the relationship, if one existed, probably would be specific to the source water.

Studies of removal of Giardia cysts and cyst models by DE filtration were first reported by Logsdon et al. (1981a). The raw water was a low turbidity surface water obtained from a local gravel pit. The first studies were performed with 9 um radioactive microspheres, and results indicated that removal of 9 um particles bore little relationship to turbidity removal. Use of an adequate amount of DE precoat and application of DE body feed during the run were more important than attaining a specific filtered water turbidity goal. The manner of operation of the filter, rather than turbidity removal as measured by a nephelometer, was the key factor for attaining over 99.9 percent removal of 9 um particles. Later studies at EPA showed that a DE filter with adequate precoat and a clean septum could consistently remove more than 99 percent of the G. muris cysts applied to the filter.

TABLE 17. Average Removal Percentages of Total Coliform Bacteria, Standard Plate Count Bacteria, Turbidity, Particles, and *Giardia* Cysts and Average Rate of Pressure for Seven Grades of Diatomaceous Earth

Grade of Diatomaceous Earth	Celite 545®	Celite 535®	Celite 503®	Hyflo Super-Cel®	Celite 512®	Standard Super-Cel®	Filter Cel®
Number of tests	15	2	10	4	2	3	2
Median Particle Size (um)	26.0	25.0	23.0	18.0	15.0	14.0	7.5
Total Coliform Removal (%)	49	85	69	92.6	97.9	99.90	99.86
Standard Plate Count Removal (%)	58	80	69	75	79	99.1	99.85
Turbidity Removal (%)	13	12	12	24	31	50	97.6
Particle Count Removal (%)	94.4	90.2	92.14	87.4	ND[1]	ND	ND
Giardia Cyst Removal (%)	>99.7	>99.5	>99.7	>99.4	ND	ND	ND
Average Rate of Pressure Increase (cm Hg/hr)	0.693	0.100	0.289	0.065	0.510	2.71	21.04

[1] No data (ND) taken for this measurement

From: Lange *et al.* (1984)

TABLE 18. Removal Percentages of Total Coliform Bacteria, Standard Plate Count Bacteria, and Turbidity for Two Diatomaceous Earth Grades Coated at Various Alum Concentrations

Grade	Conc. of Alum (%)	Average Removals Total Coliform (%)	Standard Plate Count (%)	Turbidity (%)
Celite 545®	2	-	-	66
	4	99	95	86
	5	99.86	98.56	98.4
Celite 503®	5[1]	98	79	79
	5	99.56	93	94.4
	5[2]	96	99.57	98.6
	8	99.83	99.52	98.8

[1] Bodyfeed concentration was increased to 50 ppm after 3 hours of testing at 25 ppm

[2] Bodyfeed concentration 50 ppm, all other bodyfeed rates were 25 ppm

From: Lange *et al*. (1984)

Research with *G. lamblia* cysts at the University of Washington confirmed these results (DeWalle, 1983). Table 20 shows that diatomaceous earth filtration was very effective for *Giardia* cyst removal. More than 99 percent of the cysts were removed in every one of the 12 filtered water samples analyzed in this series of tests. Filtered water turbidity had little relationship to cyst removal.

Lange *et al*. (1984) also studied *Giardia* cyst removal by DE filtration. The only run (of 26) in which cysts were detected was the run with a very high cyst concentration, 34,000 cysts per liter. When cyst concentrations ranged from 100 to 10,000 cysts/L, no cysts were detected in the filtered water. Results in Table 21 show that DE filtration is effective for cyst removal at rates of 2.4 to 9.8 m/hr. These experiments were performed with Horsetooth Reservoir water, which had very fine turbidity-causing particles. The data in Table 21 very clearly show that cyst removal efficiency was not related to turbidity removal by DE filters.

Field tests for removal of *Giardia* cysts were performed at the Cache la Poudre River and at Dillon, Colorado. Celite 545® was used in all tests. Results are given in Table 22. During one of the six filter runs, cysts passed through

TABLE 19. Average Removal of Bacteria and Turbidity for Seven Diatomaceous Earth Filtration Field Test Runs Using Celite 545®

Water Source & Run Duration (min)	Test Conditions			Measurement								
				Total Coliform			Standard Plate Count			Turbidity		
	Temperature (°C)	Hydraulic Loading Rate (m/hr)	Rate of Pressure Increase (cm Hg/hr)	Influent (No/100 mL)	Effluent (No/100 mL)	Removal (%)	Influent (No/mL)	Effluent (No/mL)	Removal (%)	Influent NTU	Effluent NTU	Removal (%)
Poudre (145)	9	2.44	0.00	100	3	97.0	35,000	5,750	84	3.7	0.99	73
Poudre (210)	9	2.44	35.00	7,000	1,625	77.7	26,500	3,438	87	32.0	7.30	77
Dillon (105)	3.5	2.44	2.40	ND	ND	-	ND	ND	-	0.66	0.42	36
Dillon (65)	3.5	2.44	3.77	3,500	1,000	71	6,000	1,025	83	2.4	1.46	39
Dillon (300)	3.5	2.44	0.27	1,875	891	51	408	141	65	0.86	0.68	21
Dillon (90)	3.5	4.88	2.20	2,500	1,450	42	1,075	800	26	0.55	0.43	22
Dillon (75)	3.5	9.76	13.33	3,500	1,500	57	1,100	900	18	0.58	0.34	41

From: Lange *et al.* (1984)

TABLE 20. Comparison of *Giardia lamblia* Cyst Removal and Filtered Water Turbidity for Diatomaceous Earth Filtration

Run No.	Polymer Added	Cyst Addition Method		Elapsed Time (Hrs:Min)	Cyst Removal (%)	Filtered Water Turbidity (NTU)
		Slug	Continuous (Cysts/L)			
63	No	$3.0 \cdot 10^6$		0:05	99.35 to < 99.78	1.0-0.68
		$3.0 \cdot 10^6$		0:20	> 99.65	0.57-0.54
		$3.0 \cdot 10^6$		2:00	> 99.65	0.44-0.46
			$1.5 \cdot 10^5$	2:30	99.61 to < 99.96	0.48-0.55
			$9.0 \cdot 10^5$	3:00	99.03 to < 99.10	1.90-2.24
64	Yes	$3.0 \cdot 10^6$		0:05	99.61 to < 99.96	1.0-0.6
		$3.0 \cdot 10^6$		0:20	> 99.65	0.52
		$3.0 \cdot 10^6$		2:00	> 99.65	0.18-0.22
			$1.5 \cdot 10^5$	2:30	> 99.65	0.23-0.29
			$9.0 \cdot 10^5$	3:00	99.48 to < 99.56	0.60-1.11
65	No		$4.5 \cdot 10^5$	3:00	99.83 to < 99.94	0.68-1.02
66	Yes		$4.5 \cdot 0^5$	3:00	99.87 to < 99.99	0.57-0.80

From: DeWalle *et al*. (1983)

TABLE 21. Giardia Cyst and Turbidity Data for Diatomaceous Earth Filtration Tests

Run No.	Celite® Grade	Filt. Rate (m/hr)	Temp. (°C)	Length of Test (min)	Influent Giardia Cyst Concentration: Added to Feed Water (cysts/L)	Influent Giardia Cyst Concentration: Detected in Feed Water (cysts/L)	No. of Cysts Detected in Effluent Sample (No.)	Effluent Giardia Concentration (cysts/L)	Giardia Cyst Percent Removal (%)	Turbidity: Influent NTU	Turbidity: Effluent NTU
13	545	2.44	5	90	100	27.7	0	<0.701	>99.299	3.5	3.3
18	545	2.44	13	90	100	50.5	0	<0.461	>99.539	4.2	3.6
20	545	2.44	5	90	500	229.0	0	<0.465	>99.907	4.4	3.5
28	545	2.44	5	340	770	75.0	0	<0.326	>99.958	4.6	3.8
42	545	2.44	13	145	10,000	-	0	<0.112	>99.998	9.1	6.9
43	545	2.44	15	150	5,460	-	0	<0.108	>99.998	-	-
45	545	2.44	14	260	8,850	-	0	<0.063	>99.999	-	-
41	545	2.44	12	55	3.36×10^4	-	1,700	25.148	99.925	-	-
49	545	2.44	10.5	980	2,467	-	0	<0.0004	>99.999	9.9	8.4
14	545	4.88	5	90	100	44.4	0	<0.425	>99.575	3.5	3.4
19	545	4.88	13	90	100	65.9	0	<0.323	>99.677	4.4	3.6
21	545	4.88	5	90	500	330.0	0	<0.326	>99.935	4.4	3.6
17	545	9.76	5	90	100	47.0	0	<0.443	>99.557	4.2	3.7
26	545	9.76	5	90	500	31.5	0	<3.342	>99.332	4.2	3.8
15	535	2.44	5	90	100	45.5	0	<0.423	>99.577	3.6	3.2
16	535	4.88	5	90	100	45.5	0	<0.453	>99.547	3.6	3.1
11	503	2.44	5	90	100	76.4	0	<0.257	>99.743	3.5	3.3
25	503	2.44	5	90	500	127.0	0	<0.691	>99.862	4.4	3.7
44	503	2.44	15	275	5,460	-	0	<0.058	>99.998	-	-
12	503	4.88	5	90	100	40.0	0	<0.481	>99.519	3.6	3.3
22	503	4.88	13	90	100	59.0	0	<0.357	>99.643	4.2	3.6
24	503	4.88	5	90	500	127.0	0	<0.895	>99.821	4.3	3.5
27	503	9.76	13	90	100	33.0	0	<0.532	>99.468	4.2	3.7
9	Hyflo	2.44	5	90	100	41.4	0	<0.478	>99.522	3.7	3.0
10	Hyflo	4.88	5	90	100	27.2	0	<0.694	>99.306	3.5	3.1
45	545	4.88	14	40	8,850	-	0	<0.408	>99.995	6.6	-

From: Lange *et al.* (1984)

TABLE 22. *Giardia* Cyst and Turbidity Data for Diatomaceous Earth Filtration Field Tests

Run No.	Grade	Filt. Rate (m/hr)	Temp. (°C)	Length of Test (min)	Influent *Giardia* Cyst Concentration		No. of Cysts Detected in Effluent Sample (No.)	Effluent *Giardia* Concentration (cysts/L)	*Giardia* Cyst Percent Removal (%)	Effluent Turbidity NTU
					Added to Feed Water (cysts/L)	Detected in Feed Water (cysts/L)				
F1	C-545	2.44	10	145	3,950	-	0	<0.162	>99.996	0.99
F2	C-545	2.44	9	210	1,650	750	80	9.254	99.439	7.3
F3	C-545	2.44	3.5	105	1,000	229	0	<0.385	>99.962	0.42
F4	C-545	9.76	3.5	75	500	312	0	<0.216	>99.931	1.46
F5	C-545	4.88	3.5	90	1,000	740	0	<0.109	>99.989	0.43

From: Lange *et al*. (1984)

the filter. When the filter was then subjected to leak testing, existence of a leak was confirmed. During the five runs with no leaks, no cysts passed through the DE filter. Comparison of cyst removal results with filtered water turbidity measurements again showed that removal of cysts was not related to removal of the smaller sized turbidity-causing particles, except perhaps in the case of an equipment malfunction. The turbidity of the filtered water in run F-2, the run in which a leak occurred, was 7.3 NTU. When DE equipment is properly maintained, this filtration process is capable of removing well over 99.0 percent of *Giardia* cysts from raw water. Process efficiency is related to proper operation and maintenance of equipment rather than to effluent turbidity.

During the latter half of the Duluth pilot plant study, pressure DE filtration repeatedly produced water with turbidity of 0.10 NTU or lower. The grade of diatomite selected should be fine enough to produce a filtered water of 0.10 NTU or lower, because high fiber counts were usually associated with turbidities above 0.10 NTU (Fig. 18). Nine of twelve BDL counts occurred with turbidities of 0.10 or lower. Until other data are developed showing that effective amphibole fiber removal can occur at turbidities above 0.10 NTU, this level of turbidity should be the operating goal for DE filtration plants.

Removal of chrysotile asbestos has been studied in Canada (Lawrence, 1977). Removals of 99.9 percent were observed for uncoated diatomite, whereas use of alum coated diatomaceous earth yielded chrysotile removals exceeding 99.99 percent. Lawrence did not present turbidity data, but little reason exists to suspect that chrysotile removal would be effective with effluent turbidities above 0.10 NTU. This would need to be verified by on-site pilot plant studies before a DE filtration plant was built and operated for the purpose of removing chrysotile fibers from water.

RELATIONSHIP OF TURBIDITY TO DISTRIBUTION SYSTEM WATER QUALITY

Under the current regulations, turbidity is recorded or measured daily from samples taken at a representative entry point to the distribution system. Turbidity changes that can occur in the distribution systems are not regulated. Turbidity monitoring within the distribution system has been recommended recently by two of the panels assembled by the U.S. EPA Office of Drinking Water to propose revisions in drinking water regulations on microorganisms and turbidity (Sobsey, 1983, Olivieri, 1983). Both groups indicated that turbidity monitoring along with the other tests would detect water quality degradation and recontamination due to bacterial regrowth and colonization, deterioration of distribution pipes and entrance of external contaminants by broken or leaky pipes, maintenance and repair operations and cross connections. Neither group recommended a specific turbidity MCL for water in distribution systems. Increased turbidity and microbiological levels in dead end stagnant portions of distribution systems are frequently observed and increases in turbidity and bacterial counts during transmission through constantly flowing mains also have been shown (Olson, 1982). However, Reilly and Kippin (1983) reported that neither standard plate count densities nor frequency of coliform isolation from distribution system samples were correlated with turbidity levels. Another panel (Pipes, 1983) recommended maintaining the

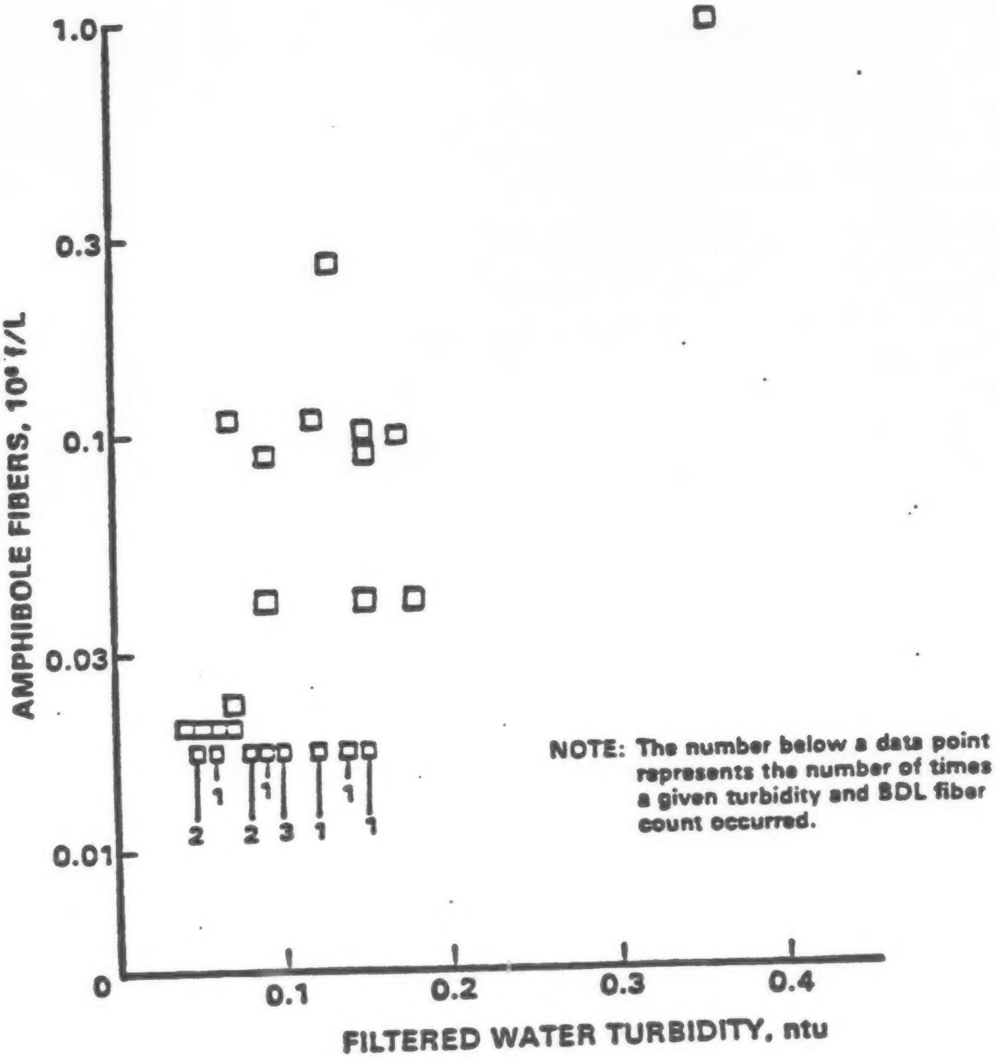

Figure 18 Effluent turbidity vs. amphibole fiber count for pressure diatomite filtration — Duluth pilot plant.

From: Logsdon, (1979)

current regulation on point of measurement although in another portion of their report they indicated that because of the possible interference of high turbidities with coliform detection, ". . . it would be reasonable to make turbidity measurements on the samples collected for microbiological examination."

It would appear that most important health related basis for turbidity monitoring in distribution systems would be the detection of recontamination of the water from outside the system. Pipes (1982) describes the physical integrity of the distribution system as the most difficult barrier to maintain and the one whose penetration poses the greatest threat of waterborne disease. The prospect of distribution system contamination from outside sources provides the major basis for coliform monitoring within the distribution system. Monitoring chlorine residual also has been considered as a simple rapid method for detecting this type of contamination and the current regulation provision for substituting chlorine residual measurement for coliform sampling in distribution is based in part on this concept. Comparative studies of the ability of these three measurements for detection of extraneous contamination apparently have not been done. In the absence of such comparative studies, it is difficult to determine the value of turbidity measurement for detecting such contamination.

SUMMARY

Research shows that the relationship for turbidity and quality of filtered water is different for each the three filtration processes evaluated, so each is discussed separately in this section.

Properly designed and operated granular media filtration plants have the capability of removing a variety of particulate contaminants, ranging in size from asbestos fibers and viruses to bacteria to cysts. When water is treated by coagulation and rapid rate filtration, effective pretreatment is necessary. Consistent, removal of particulate contaminants can be accomplished only if the water is coagulated properly before it is filtered. When proper coagulation is performed, the research data cited in this Section suggest that an appropriate filtered water turbidity goal for clear source waters is 0.10 NTU. A 1 NTU raw water should be filtered to produce 0.10 NTU. For raw waters above 5 NTU, the 0.1 NTU goal may be less appropriate. Further research or analysis of operating experience is needed to resolve this matter.

Results of a number of recent studies indicated that slow sand filtration effectively removed Giardia cysts and coliforms as well as turbidity. In another study, slow sand filtration effectively removed microorganisms but did not substantially reduce the turbidity. This raw water source contained many fine particles (less than 1 um) of kaolinite and montmorillonite clay that were not readily removed by filtration. Thus, the usefulness of turbidity in indicating pathogen removal may be site specific.

The relationship of effluent turbidity and the quality of waters from diatomaceous earth filters is complex. DE filters can remove large particles (about 10 um) such as Giardia cysts, even when small, turbidity-causing particles pass through. Cysts appear to be removed by a straining or screening action, even when smaller particles are not removed. Surface attachment of bacteria, viruses, and asbestos can be enhanced by using alum-coated diatomite. In this situation, contaminant removal would seem to be indicated by removal of turbidity-causing particles. The Duluth pilot plant results indicate that 0.10 NTU is appropriate for removal of very small (1 um or less) particles by surface attachment on alum-coated diatomaceous earth.

V MEASUREMENT

The National Interim Primary Drinking Water Regulations state that turbidity measurement shall be made by the Nephelometric Method as described in the 15th edition of Standard Methods for the Examination of Water and Wastewater, (Standard Methods), (APHA, 1980) or Methods for Chemical Analysis of Water and Wastes, (USEPA, 1979). Standard Methods also lists the Jackson Candle Turbidimeter and a Bottle Comparison test as other methods for measuring turbidity. The latter methods can be used only for samples other than drinking water.

Standard Methods states that a 2-liter volume of sample should suffice for most analyses and that glass or plastic containers can be used for turbidity sampling. Methods of sampling are also discussed in Standard Methods as well as the preparation of turbidity free water, stock turbidity suspensions, and turbidimeter calibration. Readings are made after sufficient time is allowed for air bubbles to escape. Turbidity should be determined on the same day the sample is taken. Standard Methods does not state the accuracy or precision of turbidity measurements by the nephelometric method. It does state, however, that the instrument should measure from 0 to 40 units of turbidity and should detect turbidity differences of 0.02 NTU in waters showing turbidity less than 1 NTU. Differences in turbidimeters can be minimized if:

1. Light source has a tungsten filament operated between 85 to 100 percent of rated voltage or at a color temperature between 2,200 and 3,000 K.

2. Total distance traversed by the light path, including the path through the sample in the tube, does not exceed 10 cm.

3. The angle of light acceptance by the detector, centered at 90° to the incident light and not to exceed ± 30° from 90°.

4. Maximum turbidity measurement is 40 NTU.

Raw water supplies can contain inorganic particles such as clay, silt or asbestos fibers and organic particles such as humic substances, viruses, bacteria and plankton. It is well established that turbidity cannot be used to measure the amount of suspended material in water unless the relationship between the particle size distribution and total suspended mass is known (Lohring and Booth, 1975; Hach, 1975). Edzwald (1983) pointed out that the size, type and concentration of particles can have a profound effect on the turbidity of water. Small particles with dimensions of less than 0.1 um do not scatter much visible light so that water containing small inorganic or organic particles could contain large numbers of particles but give a low turbidity reading. Larger particles such as clays or plankton with particle diameters approximately that of the wavelength of visible light scatter light more effectively and would yield higher turbidities. This is illustrated in Fig. 19 (Edzwald, 1983), showing that 50 mg kaolinite/L gave a turbidity reading of about 80 NTU, while 50 mg humic acid/L gave a turbidity reading of only slightly more than 3 NTU.

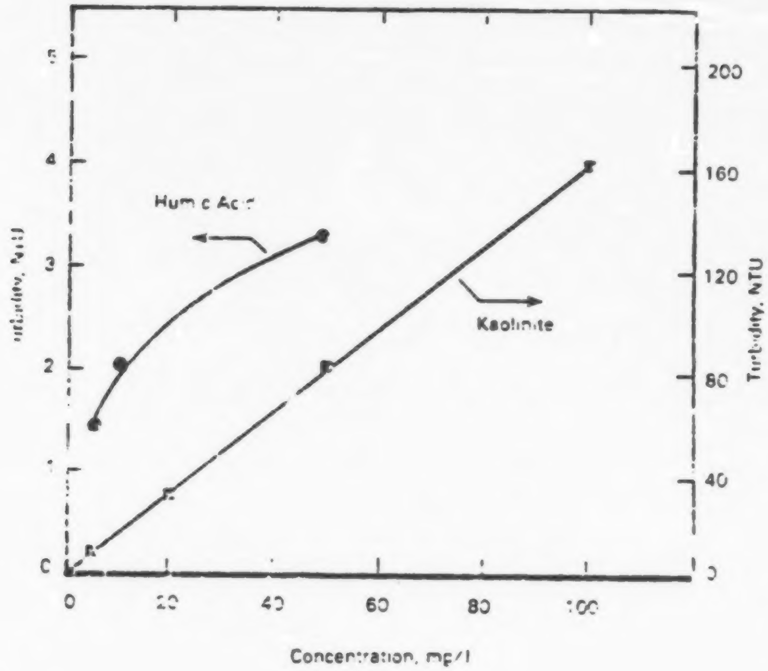

Figure 19. Turbidity vs. solids concentration for humic acid and kaolinite

From: Edzwald, (1983)

In a study of the measurement variability of turbidity, color and odor in water, Harris (1972) prepared four basic water samples and sent them to 15 water plant operators (3 water plants) for analysis. The operators were to analyze the samples according to the 13th edition of Standard Methods (APHA, 1971). The samples for turbidity analysis were prepared from Fuller's Earth and distilled water and contained 1, 5, 15 and 35 TU. The medians of the distributions of the measured values were 0.9, 4.8, 18 and 33 TU. The results of this study showed good precision between replicate samples but the measurement systems were least reliable with the low turbidity samples.

In Methods for Chemical Analysis of Water and Wastes (USEPA, 1979), the U.S. EPA Environmental Monitoring and Support Laboratory (EMSL) reported that their laboratory tested surface water with turbidities of 180, 75, 41, and 26 NTU. The standard deviations were ± 4.7, ± 1.2, ± 0.94 and ± 0.60 respectively.

In a more recent study by EMSL, turbidity quality assurance samples were prepared from formazin. The samples contained either 7 or 1 Turbidity Units (NTU) and both samples were sent to State and USEPA laboratories for analysis. The results showed that the sample containing 7 NTU's had a standard deviation of ± 0.407 (38 laboratories). The standard deviation for the 1 NTU sample was ± 0.183 (37 laboratories). McGirr (1974) studied the variability of turbidity measurement of water samples from 27 laboratories. He found that lower turbidity readings occurred as the samples aged and storage instability was the most serious limitation on samples shipped to the laboratory. Other variables were differences in preparation of turbidity standards and laboratory differences in shaking the sample before analysis.

Katz (unpublished data) determined the turbidity of 89 different raw water samples and repeated the analysis after 24 hours storage at room temperature. The results (Table 23) showed that the turbidity of samples can change with storage at room temperature. Some samples increased in turbidity, others decreased and there was no change in about 33 percent of the samples. There appeared to be no correlation of the changes with the initial turbidity measurement.

TABLE 23. Turbidity Changes in Raw Water Samples After Storage for 1 Day at Room Temperature

Initial Turbidity (NTU)	Number of Samples	Turbidity Changes After Storage					
		Increased		Decreased		No Change	
		No.	Percent	No.	Percent	No.	Percent
0.05-1	22	8	36	5	23	9	41
>1 - 5	39	21	54	6	15	12	31
> 5	28	10	36	11	39	7	25

From: Katz (Unpublished data)

The manufacturer of the Hach Turbidimeter Model 2100A states that this instrument when calibrated with formazin standards and using a 30 ml sample has an accuracy of ± 2 percent of full scale and a reproducibility of ± 2 percent of full scale with a stray light correction of - 0.04 TU on the low ranges. The Hach Company also manufactures a Ratio Turbidimeter. They claim that this instrument can measure turbidities less than 0.05 NTU with an accuracy of ± 0.01 NTU (Hach, 1983). Water regulations now permit calibration of turbidimeters with formazin or a suspension of styrene divinylbenezene (Federal Register, 1982).

The water regulations require that community drinking water systems be monitored daily for turbidity. Because particles in water contribute to the turbidity, researchers have an interest in particle characterization particularly as to their size, number and type. Hannah *et al.* (1967) reported that particle counting provided a more quantitative evaluation of the suspended matter in finished water than turbidity measurement. Tate and Trussell (1978) evaluated three particle counters and one particle size analyzer. They selected the particle size analyzer as the instrument best suited for their study of the unit processes in a pilot water treatment plant. The water quality objective of their study was the production of treated water with a 0.2 TU and 50 particles (2.5 - 150 micrometers) per mL as a maximum acceptable level. They reported that the particle counting technique was a useful complement to the turbidity measurements in pilot plants. The technique could also be used for calculations of specific deposits in filters and for optimizing operating parameters for unit processes. They stated "For optimal disinfection the superior alternative is one with fewer and smaller particles".

Beard and Tanaka (1977) compared particle counting and turbidity measurements as tools to evaluate the various stages of water treatment for two conventional filtration plants that were treating low turbidity source water. Their preliminary results from bench scale tests showed that samples for particle analysis were relatively stable for three to four days under refrigeration. Samples stored under ambient conditions, however, showed changes in particle concentration and size within 24 hours. Particle stability was dependent on storage time, temperature and coagulant type. At treatment plants that used relatively clear source water they found that sedimentation of treated water had a minor effect on the concentration of particles but this step did lower the turbidity readings. The best treatment for overall removal of suspended matter utilized a cationic polymer at a dosage of 0.4 mg/L. This treatment reduced the total number of particles and reduced the maximum particle size to between 1 and 15 um. They stated that ". . . particles in this size range should not interfere with the disinfection process". They concluded that particle counting is more sensitive to changes in source water quality and process variables than turbidity measurement. Kavanaugh _et al._ (1980) used particle counts and turbidity measurements in pilot plant studies of direct filtration. They found that particle counts in filter effluents began to increase several hours before the turbidity of the effluent increased. An increase in turbidity of the effluent is normally used to signal the end of a filter run. They also found that the number of small particles (2.5-10 um) in the effluent began to increase before the number of large particles increased. They stated "It is likely that accurate process control and monitoring of solids/liquid separation processes will require both turbidimetric and particle size distribution measurements. Particle counting appears most promising as a feedback control sensor". Monscvitz and Rexing (1983) reported on the use of 5 on-line particle counters with 25 remote sensors for operational control of particulate removal at a water treatment plant in Nevada. A computer station with 32 remote terminal units was also installed to handle the massive amount of data generated by the particle counters. Through the use of a small pilot plant and particle counter, the optimum chemical dosage for single and dual coagulants was determined for the source water. The optimum dosage resulted in a 32 percent savings in chemical costs. By using a particle counter, they also determined that the filters should be backwashed whenever the particle count of the filter effluent was greater than 20 particles/mL. They proposed " . . . on-line particle counting as a substitute for turbidity monitoring to control a direct filtration water treatment plant." Thus, particle counters may be economically feasible for control of unit processes in water treatment plants where the water source has a relatively low particle count. However, more research needs to be done where the source water has a high particle concentration covering a wide range of particle sizes. Silverman et al. (1983) used particle counts as one of several parameters to characterize the particulate matter in an uncovered finished drinking water reservoir. They found that the quality of the influent was often better than the quality of the effluent primarily due to biological activity in the reservoir. They stated that "Changes in the number, size and shape of suspended particles may indicate a change in water quality that might not be reflected by turbidity values" and ". . . measurement of particulate material may offer ways for better characterizing water quality" than turbidity measurements.

Hoff (1978) showed that washed primary effluent solids or cell culture debris diluted to contain 5 or 1 TU interferes with the rate of viral and bacterial inactivation. Other research at the MERL Cincinnati laboratory attempted to correlate particle size and turbidity with resistance to disinfection of coliform bacteria imbedded in primary effluent solids. An advantage of particle size analysis is that it is a direct measurement of the particles in water, whereas turbidity is an indirect measurement. Ridgeway and Olson (1982) showed by scanning electron microscopy of particles retained by a 2.0 um pore size membrane filter that particles with attached bacteria were usually larger than 10 um. They reported that the number of bacteria attached to a single particle varied from 5 or 10 to as many as several hundred. Silt and clay particles found in water fall into this size range (Tate and Trussell, 1978; Beard and Tanaka, 1977; Stern and Stickle, 1978). Thus, a particle size analyzer can serve as a guide to determine the number of particles larger than 10 um in filtered water that may present disinfection problems.

SUMMARY

Drinking water regulations require that turbidity be measured by the nephelometric method. Standardized methods for turbidity measurement, including procedures for the preparation of turbidity free water, stock turbidity suspensions and turbidimeter calibration are available. Problems with turbidity measurement, including differences in measurements produced by different turbidimeters, the effects of storage time and temperature and mixing intensity on turbidity measurement, are recognized.

Particle counters and particle size analyzers are useful instruments that have been used for the study of unit processes in the water treatment train. These data can be used to optimize water treatment procedures and give advance warning of filter failure.

VI DEVELOPMENT OF TURBIDITY HEALTH GOAL

With the exception of the turbidity and coliform standards, drinking water standards deal with specific inorganic and organic chemicals and radionuclides that have been shown to produce concentration related toxic effects. In contrast, the contaminants measured by turbidity constitute an extremely diverse and variable group of substances, the great preponderance of which have no demonstrated effects on human health. The health significant particles (pathogenic microorganisms, particles containing pathogenic microorganisms or adsorbed toxic materials, asbestos) constitute a small but variable part of the total turbidity measured. Because of this lack of specificity, direct toxicity testing of "turbidity" is not useful since the results would not be broadly applicable to turbidity in waters from different sources. Turbidity should be treated as an indicator of the effectiveness of filtration to remove or inactivate harmful substances, rather than as a direct health hazard. In this way, turbidity is comparable to total coliforms. Turbidity measurements are also useful in predicting the effectiveness of disinfection.

As indicated in Section IV, the presence and concentration of health significant particles in raw water cannot be predicted using turbidity measurement alone. When used in conjunction with other information from sanitary surveys and coliform and fecal coliform counts, turbidity data can contribute to the overall assessment of raw water quality.

As a measure of the removal of health significant particles by physical water treatment processes, the significance of turbidity varies depending on the treatment used. In general, when raw water contains health significant particles, a rise in filtered water turbidity very probably is a sign of an increase of health significant particles in the filtered water but the magnitude of the increase can not be estimated on the basis of the amount of increase in turbidity. Because the different filtration processes (rapid rate granular media, slow sand, diatomaceous earth) depend on different removal mechanisms, no single relationship for filtered water turbidity and contaminant removal can be set forth. The importance of filtered water turbidity varies, depending on the filtration process being used and sometimes on the contaminant being removed.

The key mechanisms controlling particle removal in rapid rate granular media filtration are particle destabilization (coagulation) and attachment of particles to media grains. Proper coagulation is essential for this process to work effectively and dependably. Most particles in water (bacteria, clays, Giardia cysts) have negative surface charge or zeta potential. The negative charge is reduced or overcome by use of aluminum or iron salts, or by use of cationic polymers. The destabilized particles are more likely to adhere to media grains when they come in contact with them in the filter. They "stick" to media grains or to other destabilized particles that previously were removed, reducing the number of turbidity-causing particles that pass through the filter. Research with a variety of waters generally having raw water turbidities under 10 NTU has shown that when granular filtered water turbidity was 0.10 NTU or lower, effective removal of virus, bacteria, cysts and asbestos fibers was attained.

The removal of biological contaminants by slow sand filtration appears to occur by biological means, rather than primarily by physico-chemical mechanisms. Microorganisms that enter a slow sand filter are preyed upon by higher level organisms or simply find conditions for living and reproducing to be too unfavorable, and die off. Biological removal mechanisms may be less effective for removal of turbidity-causing mineral particles, such as clays. Slow sand filtration research has shown that the turbidity-causing particles of some waters can be removed by slow sand filtration, whereas others can not. In the latter case, when a sanitary survey of the watershed and treatment plant reveals that no sources of serious contamination exists, the turbidity of slow sand filter effluent is not a matter for serious concern as long as the turbidity does not interfere with a) disinfection, b) maintenance of residual disinfectant in the distribution system, and c) microbiological determinations. The 1 NTU and 5 NTU limits in the present Regulations would be appropriate for slow sand filters. Direct evidence on removal of asbestos particles by slow sand filtration is not available.

Diatomaceous earth filtration generally employs plain, or uncoated, diatomite. When uncoated diatomite is used, the main mechanism bringing about particle removal is straining. In this situation, passage of turbidity-causing particles can indicate the passage of other particles in the same size range. Most turbidity-causing particles tend to be smaller than *Giardia* cysts, however, so turbidity removal by plain diatomite does not indicate the extent of *Giardia* cyst removal. In fact, research on removal of *Giardia* cysts by DE filtration has shown repeatedly that cyst removals of >99.9 percent can be attained even though turbidity removal is variable. The data indicate that removal of bacteria and viruses by diatomaceous earth treatment also is variable and usually less efficient than *Giardia* cyst removal.

Research with alum coated diatomaceous earth has shown that by providing a surface coating and changing the surface charge of the diatomite, the filtration process can be made to effectively remove bacteria, viruses and fine particles that cause turbidity. Research in Colorado (Hendricks, 1983), plus established concepts of the behavior of granular media filtration, suggest that filtered water turbidity is important when coated diatomite is used. The alum coating enhances opportunity for surface attachment, permitting removal of particles too small to be removed by straining. The appropriate means to monitor this process would be turbidity measurement. Too few data are available at present to recommend a health goal for turbidity effluents from diatomaceous filters.

As indicated above, turbidity also can be considered as an indicator of how efficient the final disinfection unit process will be in inactivating any pathogens not separated from the water by physical removal processes. The available information regarding the protective effects of turbidity in this regard is covered in Section III. The degree of interference with disinfection efficiency created by particles in water depends to a large extent on the nature of the particles present rather than the concentration of particles as measured by turbidity. Those particles that appear to offer the most protection (organic substances) are also those most likely to be associated with fecal pathogens. Other pathogen-particle complexes (clays, inorganic substances, flocculating agents, etc.) appear to offer varying but tinguish between the types of particles present, it cannot be used alone as a precise indicator of how efficient disinfection will be with different waters. In addition to interfering with disinfection efficiency through direct protective effects, the role of turbidity in reducing the level of available disinfectant through chemical reactions has been considered. The data indicate that while the particles themselves cause little chlorine demand, there is an overall correlation between disinfectant demand and turbidity level.

Turbidity can interfere with the detection of indicator organisms by the M-F technic. Seidler and Evans (1982) showed that as turbidity increased the number of false negative samples also increased. The presence of large numbers of non-coliform organisms can mask the number of coliforms present. This may be partially due to the production of bacteriocin-like substances inhibitory to coliforms. Coliform masking increased as the turbidity of chlorinated water increased (Le Chevallier et al. 1981).

It is not possible to establish, on a scientific basis, a single finished water turbidity value that will provide equivalent health protection to all consumers. Despite the specific shortcomings of turbidity measurement as an indicator of pathogen removal and inactivation efficiency in drinking water treatment, the long standing use of this operational control measurement to determine the efficiency of water treatment processes provides historical evidence for its usefulness. In general, reduction of turbidity by water treatment processes contributes to reduction of both pathogenic microorganisms and chemical contaminants. It follows that the lower the turbidity of treated drinking water the less likely that the water will contain contaminants that may have a harmful effect on the health of consumers.

This relationship is especially strong for "conventional" treatment involving flocculation, sedimentation, filtration and disinfection. This type of treatment is used in systems serving the majority of the U.S. population. It is generally agreed that this combination of unit processes, properly conducted, will routinely produce finished water having a turbidity of 1.0 or less. It also is recognized that with additional attention and operational control of this combination of unit processes, attainment of 0.10 NTU is feasible with few exceptions. For systems using slow sand filtration and diatomaceous earth filtration, the relationship of pathogen removal to turbidity removal is less consistent and turbidity limits more difficult to establish.

The second largest population group served by surface sources receive water treated by disinfection only. Because of the inability of the turbidity measurement to assess the nature of the particles constituting the turbidity and in the current absence of any practical method for assessing particle characteristics, reduction of the particulate load as measured by turbidity is the prudent course of action. This is especially important because of the high degree of reliance placed on disinfection efficiency in these systems.

Several panels of experts recently assembled by the U.S. EPA Office of Drinking Water to propose revisions in drinking water regulations on microorganisms and turbidity recomended that the turbidity MCL of 1 NTU be retained. The AWWA recommends a turbidity goal of 0.1 NTU (AWWA, 1968). Monitoring of turbidity within the distribution system as well as at the point of entry into the distribution system has been recommended but a specific MCL has not been suggested. Because of the many ways in which turbidity increases in distribution systems may be caused, it is extremely difficult to establish a numerical limit based on health effects for turbidity within the distribution system.

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